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Book of Abstracts

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Edited by

Michael G. Rozman, Winthrop Smith, Phillip Gould, Robin Côté
University of Connecticut

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More News from Flatland: a 2D Bose gas at NIST

W. D. Phillips , P. Cladé, C. Ryu, A. Ramanathan, K. Helmerson

Joint Quantum Institute, University of Maryland and National Institute of Standards and Technology, Gaithersburg MD 20899-8424

Theoretically, a uniform, interacting, Bose gas in two dimensions is known to undergo a phase transition from a non-superfluid to a superfluid at a non-zero temperture $T_{\rm BKT}$. This Berezinski-Kosterlitz-Thouless transition occurs in a gas, a quasi-condensate without long-range order, and results in a first-order (field-field) correlation function that decays to zero at large separation only as a power law. For $T > T_{\rm BKT}$ the quasi-condensate is non-superfluid, and is fractured by free vortices into regions of near-uniform phase whose size, near $T_{\rm BKT}$, is larger than the themal deBroglie wavelength $\lambda_{\rm th}$, leading to a correlation function that decays to zero exponentially, but over a distance larger than $\lambda_{\rm th}$. For higher temperatures the gas becomes "thermal" and the correlation function decays over a distance on the order of $\lambda_{\rm th}$.

Experiments with ^{4}He films have seen signatures of the BKT transition [1]. More recently, important features of this BKT physics have been observed in experiments with a trapped (non-uniform) atomic Bose gas at the Ecole Normale Supérieure-Paris [2] [3]. Those latter experiments observed the interference between two or more planes of atoms. Changes in the contrast of interference fringes and the appearance of a bimodal density distribution after time-of-flight were seen as evidence of the BKT transition.

Using a single plane of optically trapped Na atoms (quasi-2D in the sense that there are some thermal excitations in the tight confinement direction), we have observed interference within that single plane by creating two interfering "copies" of the atomic gas using successive Raman scatterings with momentum transfer. We measure the correlation function and see a clear evolution from a thermal gas to a quasi-condensate as the atomic density increases. We also observe the density distribution after a period of time-of-flight, a procedure that in our case reveals both bimodal and trimodal distributions. We identify both the appearance of a trimodal distribution, and an abrupt discontinuity of the rate of change of the distribution width with density, as signatures of the BKT transition. Our identification of the transition point for various temperatures is in excellent agreement with theoretical predictions [4] taking into account thermal excitations in the tight confinement direction [5]. We unambiguously see a bimodal distribution in a regime where $T > T_{\rm BKT}$, the regime of the previously unobserved non-superfluid quasi-condensate.

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[3] P. Krüger, et al., Phys. Rev. Lett. **99**, 040402 (2007)
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When is a Quantum Gas a Quantum Liquid?

E. A. Cornell

NIST/JILA - University of Colorado, Boulder, CO 80309, USA

Bose-Einstein condensation was invented originally by theorists because it was too hard for them to understand superfluid helium. B.E.C. in a dilute gas was promoted as a simple theoretical model that could yield insight into the nature of superfluidity, while avoiding the messy reality of liquids, with all their strongly correlated atoms. But maybe that messiness was not such a bad thing after all. Maybe if you could dial up the messiness gradually, you could better understand the microscopic nature of a superfluid liquid. I'll report on our efforts to characterize the dispersion relation of a strongly interacting degenerate Bose gas.

Cooperative Spontaneous Emission and Scattering of Light: A Theory of Coherent Radiation Damping

Roy J. Glauber

Department of Physics, Harvard University, Cambridge, MA 02138, USA

A quantum radiated by any one of a collection of identical atoms may be absorbed by others and re-emitted many times before it emerges. The radiation is thus best described as a collective process. It takes place only in certain favored modes that have a particular range of decay lifetimes and corresponding ranges of spectral level shifts and line widths. The light that these atoms scatter resonantly also reflects this complex spectral structure.

Coherent control of matter: a multiple-photon atom interferometer to measure h/M_{Cs}, and strongly correlated (Laughlin) states in rotating Bose Condensates

S. Chu

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

This talk will summarize the current progress of two experiments. (1) A new measurement of h/M_{Cs} using multiple-photon beam splitters in an atom interferometer. Mach Zender and Ramsey-Borde atom interferometers using coherent beam splitters of up to 20 photon momenta have been recently reported by our group. Using this wide-area interferometer, progress in an improved measurement of the fine structure constant, with the goal of measuring the 2 kHz photon recoil frequency shift to an absolute accuracy of less than 2 micro Hertz will be presented.

In the second half of the talk, our studies of rotating Bose gases will be presented. The correlated motions of rotating atoms are directly analogous to the Fractional Quantum Hall effects of 2-D electrons in a magnetic field in that both systems exhibit a new quantum ground state where a motionally-correlated ground state arises from single particle degeneracy. I will discuss our experimental efforts to populate strongly correlated, higher angular momentum states in micro-Bose condensates.

Herbert Walther, scientist extraordinaire

Pierre Meystre

B2 Institute, Department of Physics and College of Optical Sciences
The University of Arizona, Tucson, Arizona 85721

Herbert Walther, a dear friend and colleague, died two years ago after a valiant battle with cancer. His contributions to all aspects of AMO science have been nothing short of extraordinary. They cover an amazing range of activities from spectacular scientific contributions to the teaching and mentoring of outstanding students, and from science politics and management to the active promotion of international scientific exchange . . . not to mention his legendary Gastfreundschaft, and Margot’s wonderful dinners. Every single one of these activities would easily have been a full-time job for most of us, but Herbert did it all superlatively and with extraordinary energy, dedication and grace. The talk will attempt the impossible task of highlighting in a few minutes the key milestones of this extraordinary career, and the route that led from a childhood in war-torn Germany to building the premier quantum optics institution in the world.

Willis E. Lamb Jr. (July 12, 1913 - May 15, 2008)

P. R. Berman

Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

Willis Lamb contributed in a profound way to our understanding of the interaction of radiation with matter. In this memorial talk, I will highlight some of his many achievements in the fields of atomic and laser physics.

Precision atom interferometry

M. A. Kasevich

Department of Physics, Stanford University, Stanford, California 94305, USA

This talk will summarize recent experimental and theoretical progress in the development of atom de Broglie wave sensors and methods for applications in navigation, geodesy and fundamental physics. Navigation and geodetic sensors include gyroscopes, accelerometers and gravity gradiometers. Fundamental physics sensors include a 10 m fountain apparatus for tests of the Equivalence Principle and post-Newtonian gravitation, and proposals for terrestrial and space-based gravity wave detectors. Finally, recent progress toward implementation of sub-shot noise atom interferometry methods will be discussed.

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

G. Gabrielse

Harvard University, Cambridge, MA 02138
gabrielse@physics.harvard.edu

A new measurement[1] gives the electron magnetic moment in Bohr magnetons,

$$g/2 = 1.001\,159\,652\,180\,73\,(28)\,[0.28\,\mathrm{ppt}].$$

The uncertainty is 2.7 and 15 times smaller than for measurements in 2006[2] and 1987[3]. The new measurement and QED theory determine the fine structure constant[1,4],

$$\alpha^{-1} = 137.035\,999\,084\,(51)\,[0.37\,\mathrm{ppb}].$$

The uncertainty is 20 times smaller than for independent determinations[5,6] of α.

A one-electron quantum cyclotron[7] is used, realized within a cylindrical Penning trap cavity[8] invented to inhibit spontaneous emission in such measurements. An invariance theorem[9] circumvents the leading unavoidable imperfections of the trap. A QND coupling to a one-particle self-excited oscillator[10] allows detection and quantum jump spectroscopy.

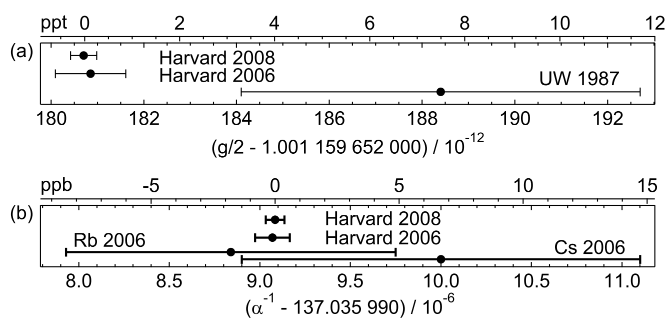

Figure 1: *New measurements of the dimsionless magnetic moment of the electron (a) and of the fine structure constant (b).*

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Determination of the fine structure constant with atom interferometry and Bloch oscillations

M. Cadoret[1], E. de Mirandes[1], P. Cladé[1], S. Guellati-Khélifa[2], C. Schwob[1], F. Nez[1], L. Julien[1], F. Biraben[1]

[1]*Laboratoire Kastler Brossel, ENS, CNRS, UPMC, 4 place Jussieu, 75252 Paris CEDEX 05, France*
[2]*Institut National de Métrologie, Conservatoire National des Arts et Métiers, 61 rue Landy, 93210 La plaine Saint Denis, France*

The fine structure constant α sets the scale of the electromagnetic interaction so it can be determined in different domains of physics. As α is dimensionless, it does not depend on any unit system. Hence this allows the comparison of various accurate determinations which constitutes an interesting test of the consistency of physics. The most precise determination of α comes from the measurement of the electron magnetic moment anomaly a_e, but this determination is strongly dependent on QED calculations. There are many reasons to realize an other determination of α. (i) The CODATA value is determined mainly by only one value of α, this is a true weakness. (ii) The comparison of $\alpha(a_e)$ with another measurement which is weakly dependent on QED provides an accurate test of QED. (iii) Assuming QED is exact, a determination of α with the same uncertainty as $\alpha(a_e)$ gives an upper limit upon a possible internal electron structure.

We report a new measurement of the atomic recoil using atom interferometry and Bloch oscillations (BO) in a vertical accelerated optical lattice. Such a measurement yields to a determination of h/m (m is the mass of the atom) which can be used to obtain a value of the fine structure constant following the equation:

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m}{m_e}\frac{h}{m} \tag{1}$$

where the Rydberg constant R_∞ and the mass ratio m/m_e are precisely known.

The principle of the experiment is to coherently transfer as many recoils as possible to the atoms (i.e. to accelerate them) and to measure the final velocity distribution. In our experiment, the atoms are efficiently accelerated by means of N Bloch oscillations. The velocity selection and velocity measurement are done with Raman transitions.

In this talk, we will present two measurements of α: a non interferometric one using two π Raman pulses[1], and an interferometric measurement with the $[\pi/2-\pi/2]$-BO-$[\pi/2-\pi/2]$ pulses arrangement. This last method leads to a determination of the fine structure constant α with a relative uncertainty of 5 ppb.

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Optical Atomic Clocks

Th. Udem

Max-Planck Institut für Quantenoptik, Garching, Germany

An optical clock consists, like any other clock, of an oscillator that defines the ticks in time and a counter that is book keeping of these periods. For a long time a quartz oscillator locked to the ground state hyperfine splitting of cesium has been used for that purpose together with an electronic counter. Clocks as different as sun dials, pendulum clocks and quartz clocks have in common that their potential accuracy increases with more rapid oscillations that slices time into finer intervals.

Tremendous advances in laser spectroscopy in the 1970’s ultimately resulted in trapped atom and ion standards in the 1980’s. When it became possible to count these optical oscillations with harmonic frequency chains in the early 1970ies, optical transitions have been considered for running optical atomic clocks. However, working with these counters was so tedious that most of the frequency chains never reached the stage where they could operate continuously even for minutes.

With the femtosecond frequency combs reliable optical counters have been realized that can now be operated continuously for months. With this the prototypes of the optical clocks can operate long enough to calibrate against cesium fountain clocks with an accuracy that is limited by the latter. Optical clocks may not only prove to be useful for industrial applications such as satellite communication and network synchronization, but could certainly play an important role in basic research. The quest or setting limits for slow variations of fundamental constants and testing relativity are examples.

In addition frequency combs may be directly used for spectroscopy by employing their narrow band individual modes. Even though single mode lasers are better suited for this purpose, frequency combs can be converted to much shorter wavelengths by the process of high harmonic generation. This might allow to access the extreme ultraviolet region which is so far unexplored with high resolution spectroscopy. Since hydrogen like ions have their sharp transitions lines in this region, fundamental research can benefit from such a development. Eventually it might even become possible to construct an X-ray atomic clock.

Comparison of Two Single-Ion Optical Clocks

T. Rosenband , D. B. Hume, P. O. Schmidt, C. W. Chou, A. Brusch, L. Lorini, W. H. Oskay, R. E. Drullinger, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, J. C. Bergquist

National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305

The single-ion mercury optical clock at NIST, Boulder has been the world's most accurate atomic clock for several years. Recently, we built a new type of optical clock that relies on quantum logic techniques to probe a single aluminum ion. Both frequency standards have fractional systematic uncertainties below 3×10^{-17}. This allows us to measure their frequency ratio (see Fig. 1) with an uncertainty of 5×10^{-17}, making this ratio the best known constant of nature[1]. By looking for changes of the ratio, we can search for changes of the fine-structure constant α. Preliminary results indicate that presently

$$\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}/\text{year},$$

which is consistent with no change.

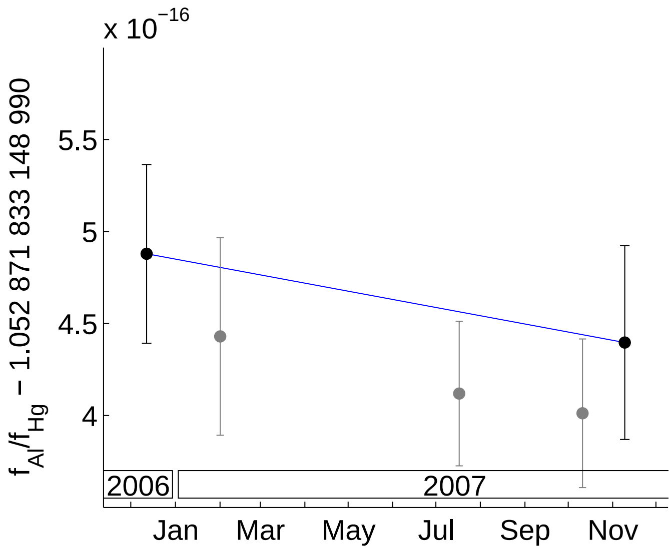

Figure 1: *History of frequency ratio measurements grouped by month. The line connects the first point to the last one with a slope of* $(-5.3 \pm 7.9) \times 10^{-17}$*/ year.*

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Precise Measurements of s-wave Scattering Phase Shifts with a Juggling Atomic Clock

S. D. Gensemer, R. Hart, Ross Martin, Xinye Xu, Ronald Legere, Kurt Gibble

Department of Physics, Penn State, University Park, PA 16802, USA

In our juggling cesium fountain clock, we have demonstrated an interferometric scattering technique that allows highly precise measurements of s-wave scattering phase shifts.[1] We juggle atoms by launching two laser-cooled clouds in rapid succession. The atoms in one cloud are prepared in a coherent superposition of the two clock states and the atoms in the other cloud are prepared in one of the $|F, m\rangle$ ground states. When the two clouds collide, the clock states experience s-wave phase shifts as they scatter off of the atoms in the other cloud. When detecting only the scattered part of the clock atom's wavefunction, the relative phase of the clock coherence is shifted by the difference of the s-wave phase shifts for the clock states. In this way, we unambiguously observe the differences of scattering phase shifts. These phase shifts are independent of the atomic density to lowest order, which enables measurements of scattering phase shifts with atomic clock accuracy. Recently, we have observed the changes in scattering phase shifts as inelastic scattering channels open and close. An ensemble of measurements will accurately test and constrain our knowledge of cesium-cesium interactions. With such knowledge, future measurements using this technique could place stringent limits on the time variation of fundamental constants, such as the electron-proton mass ratio, by precisely probing scattering phase shifts near a Feshbach resonance. [2] An overview of the current limitations to the accuracy of atomic clocks will also be presented.

Support from NASA, NSF, and ONR.

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Quantum information and non-equlibrium condensed matter physics with cold atoms

P. Zoller

Institut für Theoretische Physik, Innsbruck, Austria

We discuss scenarios of preparing entangled states of (i) cold atoms in optical lattices via driven dissipative processes [1,2], and (ii) in a hybrid system atomic / solid-state systems, which is of interest in both quantum information and condensed matter physics [3].

ad (i): Quantum optics typically considers driven open quantum system, where a system of interest is driven by an external field and coupled to an environment inducing non-equilibrium dynamics, with time evolution described by a master equation. For long times, such a system will approach a dynamical steady state, which in general will be a mixed state. However, this steady state can also be a pure state: this is achieved by an appropriate design of the system-reservoir couplings, as reflected in the "quantum jump operators" (or Lindblad operators) in the dissipative terms of a master equation, in combination with a proper system Hamiltonian. Here we are interested in extending driven dissipative state preparation of quantum states to the case of many body systems. This is of interest both as a novel way of preparing entangled states in quantum information, and suggests a new form of non-equilibrium condensed matter physics. In this talk we will focus on the latter part, including topics like (i) physical realization of reservoir engineering with cold atoms, (ii) a characterization of non-equilibrium condensed matter phases of driven dissipative systems, including phase transitions, and (iii) questions related to the dynamics of approaching the steady state.

ad (ii) We suggest to interface nanomechanical systems via an optical quantum bus to atomic ensembles, for which means of high precision state preparation, manipulation and measurement are available. This allows for a Quantum Non-Demolition Bell measurement, projecting the coupled system atomic ensemble - nanomechanical resonator into an entangled state. The entanglement is observable even for nanoresonators initially well above their ground states and can be utilized for teleportation of states from an atomic ensemble to the mechanical system. Because of the rich toolbox readily available for both of these systems, we expect the interface to give rise to a variety of new quantum protocols.

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Progress towards a quantum repeater

A. S. D. Jenkins, S.-Y. Lan, R. Zhao, A. Collins, H. Jen, Y. O. Dudin, A. G. Radnaev, C. J. Campbell, D. N. Matsukevich, T. Chanelière, T. A. B. Kennedy, A. Kuzmich

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430

Quantum mechanics provides a mechanism for absolutely secure communication between remote parties. For distances greater than 100 kilometers direct quantum communication via optical fiber is not viable, due to fiber losses, and intermediate storage of the quantum information along the transmission channel is necessary. This lead to the concept of the quantum repeater [1]. Optically thick atomic ensembles have emerged as an attractive paradigm for qubit entanglement generation and distribution, offering dramatic practical advantages compared to single-particle qubits [2]. Namely, efficient quantum state transfer between ensemble-based qubits and single photons can be achieved in free space without the need for a high-finesse cavity by utilizing a very weak interaction at a single photon/single atom level.

The first realization of coherent quantum state transfer from a matter qubit to a photonic qubit was achieved using cold rubidium at Georgia Tech in 2004 [3], followed by the first light-matter qubit conversion and entanglement of remote atomic qubits in 2005 [4].

A scheme to achieve long-distance quantum communication at the absorption minimum of optical fibers, employing atomic cascade transitions, has been proposed and its critical elements experimentally verified [5]. In order to boost communication rates, a memory-insensitive multiplexed quantum repeater has been proposed [6].

Further advances relevant to atomic ensemble based quantum networks include: Bell inequality violation between a collective atomic qubit and a photon [7], storage and retrieval of single photons [8], collapses and revivals of quantum memory [9,10], deterministic single photon sources based on quantum measurement, quantum memory, and quantum feedback [11], Hong-Ou-Mandel interference of photon pairs from two independent ensembles [12], robust entanglement of two-isotope matter qubits and frequency light qubits [13].

We will present recent experimental progress and outline future directions.

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Single atoms in optical tweezers for quantum computing

A. Browaeys , A. Gaëtan, Y. Miroshnychenko, T. Wilk, C. Tuchendler, A. M. Lance, M. P. A. Jones, J. Beugnon, G. Messin, Y. R. P. Sortais, P. Grangier

Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Univ. Paris-sud, Campus Polytechnique, RD 128, 91127 Palaiseau cedex, France

Our group is interested in neutral atom quantum computing. With this goal in mind, we have recently shown how a single rubidium atom trapped in an optical tweezer can be used to store, manipulate and measure a qubit.

I will detail in this talk how we trap and observe a single atom in an optical tweezer created by focusing a far-off resonant laser down to a sub-micron waist[1]. Our qubit is encoded on the $|0\rangle = |F = 1, M = 0\rangle$ and $|1\rangle = |F = 2, M = 0\rangle$ hyperfine sublevels of a rubidium 87 atom. We initialize the qubit by optical pumping. We read the state of the qubit using a state selective measurement limited by the quantum projection noise. We perform single qubit operation by driving a two-photon Raman transition. We have measured the coherence time of our qubit by Ramsey interferometry. After applying a spin-echo sequence, we have found an irreversible dephasing time of about 40 ms [2].

To perform a computation, a feature is the ability to perform a gate between two arbitrary qubits of the register. As a first step, we have demonstrated a scheme where the qubit is transfered between to tweezers with no loss of coherence and no change in the external degrees of freedom of the atom. We have then moved the atom over distances typical of the separation between atoms in an array of dipole traps, and shown that this transport does not affect the coherence of the qubit[3].

Finally, I will present our progress towards entangling two atoms, a key ingredient towards building a two-qubit gate. To create entanglement, we are planning to use a Rydberg blockade mechanism recently observed by several groups[4]. This blockade has also been proposed to build a phase gate[5]. I will describe the status of the experiment and show how we excite a single atom to a Rydberg state.

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Atomic physics, quantum optics, and quantum information processing with trapped ions

R. Blatt[1,2]

[1] *Institut für Experimentalphysik, Universität Innsbruck, Austria*
[2] *Institut für Quantenoptik und Quanteninformation (IQOQI), Innsbruck, Austria*

Atomic ions, confined and laser cooled in Paul traps have been the subject of intense research for decades now. Precision spectroscopy of single ions provides the basis for some of the best known optical frequency standards. Fundamental quantum optical experiments have been carried out with single laser cooled ions in Paul traps and continue to be an extremely valuable tool for an investigation of quantum feedback. Most notably, recent years have seen an increasing application of ion traps for quantum information processing. Basic quantum algorithms have been demonstrated with trapped ions and a number of quantum states have been created on demand. Such states are analyzed by state tomography, quantum procedures are characterized by process tomography and these elements provide a profound basis for the development of future quantum processors. In atomic physics, these newly developed quantum logic tools are applied for the new field of quantum metrology. Recent advances with trapped ions in the field of atomic physics, quantum optics and quantum information processing will be reviewed.

Cryogenic microfabricated ion traps: Explorations of surface physics with ions

J. Labaziewicz, Y. Ge, D. R. Leibrandt, P. Antohi, S. X. Wang, R. Shewmon, K. R. Brown, I. L. Chuang

Center for Ultracold Atoms, Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

The surface of a metal is ideally an electrical equipotential, but in reality it may exhibit significant potential variations, up to hundreds of millivolts over micrometer distances. These "patch potential" variations generate local electric fields, with a static component thought to originate from differences in the work function between crystal facets, further modified by adsorbates. The noise due to temporal fluctions of these patch fields is of considerable interest, due to broad practical implications for trapped ion quantum computation, single spin detection, and measurements of weak forces. However, surprisingly little is known about this noise, or its physical origin.

Recent experiments demonstrate that ions can be trapped with electrodes on the surface of microfabricated chips, providing a superb system for exploring the surface physics of patch potentials. [1] We present experimental results [2,3] from a family of surface-electrode ion traps, made of silver and gold metal on quartz, operated in a liquid helium cryostat. Using a single trapped $^{88}Sr^+$ ion, loaded by photoionization and sideband cooled to its motional ground state with fidelity $> 99\%$, heating rates are measured, quantifying electric field fluctuations arising from nearby trap surfaces. The ion-surface distance is varied from 75 μm to 150 μm, and the surface temperature is varied from 7 to 100 K. The noise amplitude is observed to have an approximate $1/f$ spectrum around 1 MHz, and grows rapidly with temperature as T^β for β from 2 to 4. Measured in units of motional phonons, the heating rate is found to be as low as ~ 2 quanta/sec at 6 K, which is more than 2 orders of magnitude lower then the best traps of comparable size, operated at room temperature; an identical trap operated at 300 K exhibits noise which is 7 orders of magnitude worse than at 6 K.

These results indicate that the patch fields may originate from surface fluctuators with a continuous spectrum of thermal activation energies, and suggest further experiments for trapped ions as highly sensitive probes of the physical behavior of condensed matter systems, possibly including the surface physics of superconductors.

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Cold molecular ions: Single molecule studies

M. Drewsen

QUANTOP - Danish National Research Foundation Center of Quantum Optics, Department of Physics and Astronomy, University of Aarhus, Denmark

In ion traps, the translational motion of molecular ions can effectively be sympathetically cooled to temperature in the mK range through the Coulomb interaction with laser cooled atomic ions. At such low temperatures the molecular ions typically become part of spatial ordered structures (Coulomb crystals) in which the individual molecules can be localized within a few μm^3. The extreme situation of having only a single laser-cooled atomic ion interacting with a single molecular ion is an ideal starting point for many single molecule studies. By applying a rather simple non-destructive technique for the identification of the single molecular ion in such a situations relying on an $in\ situ$ mass measurement of the molecule, we have recently studied photofragmentation of singly changed Aniline ions ($C_6H_7N^+$) as well as isotope effects in the reaction of Mg^+ ions with a H_2, HD, and D_2 molecules. In the talk, I will discuss these recent single molecular ion experiments as well as some future prospects.

Observation of light quantum jumps and time-resolved reconstruction of field states in a cavity

S. Haroche[1,2]

[1] *Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris, France*
[2] *Collège de France, Paris, France*

After a general review of recent developments in Cavity Quantum Electrodynamics, I will focus on experiments performed at ENS on microwave fields trapped during a few tenths of a second in a very high Q superconducting cavity [1].

Circular Rydberg atoms crossing the cavity one at a time are used to count trapped photons in a quantum non-demolition (QND) way, projecting in the process the field into a Fock state containing a well-defined number of light quanta [2]. The subsequent evolution of these states induced by cavity damping exhibits photon number quantum jumps observed on single field trajectories [3]. The usual exponential decay of the field energy is recovered by averaging over these trajectories, whose statistical analyzis yields a direct measurement of all the damping rates of the field master equation [4].

By using atoms to perform QND measurements on an ensemble of cavity fields prepared in the same state, we fully reconstruct this state and its Wigner function [5]. The method is applied to coherent states whose Wigner function is gaussian and to non-classical Fock and Schrödinger cat states exhibiting Wigner functions with striking non-gaussian features presenting negative values. By following the time-evolution of the reconstructed field states, we observe the progressive disappearance of these non-classical features and realize actual 'movies' of the decoherence phenomenon.

These studies in which photons are trapped and manipulated non-destructively by atomic beams can be viewed as the counterpart of ion trap experiments, in which atoms are localized in space and interrogated by laser beams. I will conclude by briefly discussing future projects generalizing these photon trap studies to two cavities and implementing quantum feedback methods to lenghten decoherence times in cavity QED experiments.

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[2] C. Guerlin *et al*, Nature **448**, 889 (2007).
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[5] S. Deléglise, I. Dotsenko, C. Sayrin *et al*, to be published.

Pseudo-Spin Squeezing on an Atomic-Clock Transition

M. H. Schleier-Smith, I. D. Leroux, V. Vuletić

Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

The best atomic clocks perform at the "standard quantum limit" set by the projection noise of uncorrelated individual two-level atoms[1]. Even higher precision can in principle be obtained from entangled ensembles[2,3,4]. In the Bloch vector representation, where the N-atom system is represented by an angular momentum $J = N/2$, such entanglement can take the form of spin squeezing[5], where the uncertainty of a component transverse to the Bloch vector is reduced below the coherent-state value $\sqrt{J/2}$.

We report measurement-induced spin squeezing on the $|F{=}1,m_F{=}0\rangle$ to $|F{=}2,m_F{=}0\rangle$ hyperfine clock transition in a sample of ^{87}Rb atoms trapped inside an optical resonator. After preparing a superposition of clock states with a $\pi/2$ pulse, we non-destructively measure the atom number difference between the two states. The measurement is performed by observing the frequency shift of one resonator mode induced by the atomic-state dependent index of refraction. Such measurement-induced squeezing requires the optical depth OD of the sample to be large. In our present system, $OD \leq 6000$.

We observe 7 dB of spin squeezing at a modest measurement-induced reduction in clock fringe visibility, corresponding to an improvement in clock sensitivity due to the squeezing. We discuss current limitations and possible future improvements, including an implementation with higher clock accuracy using magnetically trapped atoms[6,7] We believe that such squeezing methods hold great promise for further increasing the accuracy of optical clocks in a magic-wavelength optical lattice[8,9]

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Quantum micro-mechanics with ultracold atoms

D. M. Stamper-Kurn[1,2]

[1]*Department of Physics, University of California, Berkeley, CA 94720, USA*
[2]*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Isolated atoms and ions have been inserted into high-finesse optical resonators for the study of fundamental quantum optics and quantum information. Here, I will introduce another application of such a system, as the realization of cavity optomechanics where the collective motion of an atomic ensemble serves the role of a moveable optical element in an optical resonator. Compared with other optomechanical systems, such as those incorporating nanofabricated cantilevers or the large cavity mirrors of gravitational observatories, our cold-atom realization offers immediate access to the quantum regime. Experimental investigations of optomechanical effects, such as the bistability of collective atomic motion and the first quantification of measurement backaction for a macroscopic object, will be presented, along with recent progress in this nascent field.

This work was performed in collaboration with group members T. Botter, D. Brooks, S. Gupta, Z.-Y. Ma, K.L. Moore, K.W. Murch and T. Purdy, and is supported by the NSF and AFOSR.

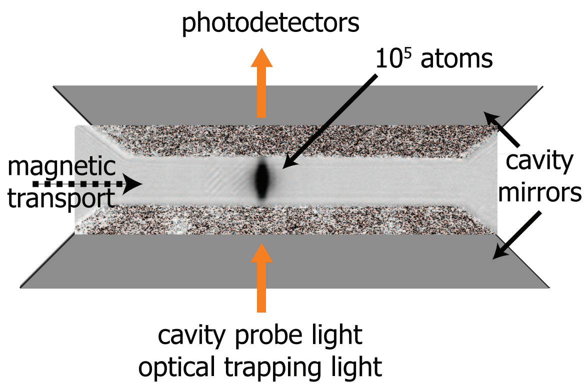

Figure 1: *The paradigmatic system of a mechanical oscillator coupled to a single mode of light is realized at a macroscopic level by trapping a large atomic ensemble within a high-finesse optical resonator. A single mode of collective atomic motion is actuated by the cavity field and measured by its optical properties. Establishing this connection allows us to explore issues related to weak force sensing by micromechanical cantilevers and by gravity-wave observatories.*

Quantum metrology with lattice-confined ultracold Sr atoms

J. Ye

JILA, National Institute of Standards and Technology and University of Colorado Boulder, CO 80309-0440, USA

Quantum state engineering of ultracold matter and precise control of optical fields have allowed accurate measurement of light-matter interactions for applications in precision tests of fundamental physics. State-of-the-art lasers now maintain optical phase coherence over one second. Optical frequency combs distribute this optical phase coherence across the entire visible and infrared parts of the electromagnetic spectrum, leading to direct visualization and measurement of light ripples. An the same time, ultracold atoms confined in an optical lattice of zero differential-Stark-shift between two clock states allow us to minimize quantum decoherence while strengthening the clock signal. For ^{87}Sr, we achieve a resonance quality factor $>2\times10^{14}$ on the $^1S_0$ - $^3P_0$ doubly forbidden clock transition at 698 nm [1]. The uncertainty of this optical atomic clock has reached 1×10^{-16} and its instability approaches 1×10^{-15} at 1 s. [2] These developments represent a remarkable convergence of ultracold atoms, optical phase control, and ultrafast science. Further improvements are still tantalizing, with quantum measurement and precision metrology combining forces to explore the next frontier.

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Quantum control of spins and photons at nanoscales

M. D. Lukin

Physics Department, Harvard University, Cambridge MA 02138, USA

We will discuss our recent work on developing new approaches for quantum control of single spins and single photons localized to nanometer dimensions. Novel applications of these techniques to problems such as nanoscale magnetic sensing will be described.

Anderson localization of matter waves

P. Bouyer

Laboratoire Charles Fabry de l'Institut d'Optique, Campus Polytechnique, rd 128, 91127 PALAISEAU CEDEX, France

email : philippe.bouyer@institutoptique.fr*; URL :* www.atomoptic.fr

In 1958, P.W. Anderson predicted the exponential localization[1] of electronic wave functions in disordered crystals and the resulting absence of diffusion. It has been realized later that Anderson localization (AL) is ubiquitous in wave physics[2] as it originates from the interference between multiple scattering paths, and this has prompted an intense activity. Experimentally, localization has been reported in light waves [3] microwaves[4], sound waves[5], and electron gases[6] but to our knowledge there is no direct observation of exponential spatial localization of matter-waves (electrons or others). We present here the observation of Anderson localization[7] of a Bose-Einstein condensate (BEC) released into a one-dimensional waveguide in the presence of a controlled disorder created by laser speckle. We also show that, in our one-dimensional speckle potentials whose noise spectrum has a high spatial frequency cut-off, exponential localization occurs only when the de Broglie wavelengths of the atoms in the expanding BEC are larger than an effective mobility edge corresponding to that cut-off. In the opposite case, we find that the density profiles decay algebraically[8].

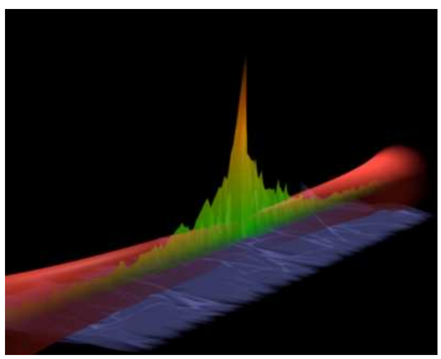

Figure 1: *Observation of Anderson localisation in 1D with an expanding Bose-Einstein Condensate in the presence of a 1D speckle disorder.*

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Anderson localization of a non-interacting Bose-Einstein condensate

G. Roati, C. D'Errico, L. Fallani, M. Fattori, C. Fort, M. Zaccanti, G. Modugno, M. Modugno, M. Inguscio

LENS and Department of Physics, University of Florence, Italy

One of the most intriguing phenomena in physics is the localization of waves in disordered media. This phenomenon had originally been predicted by P. W. Anderson, fifty years ago, in the context of transport of electrons in crystals[1], but it was never directly observed for matter waves. Ultracold atoms open a new scenario for the study of disorder-induced localization, due to the high degree of control of most of the system parameters, including interaction. For the first time we have employed a noninteracting ^{39}K Bose-Einstein condensate (BEC) to study Anderson localization[2]. The experiment is performed with a 1D quasi-periodic lattice, a system which features a crossover between extended and exponentially localized states[3] as in the case of purely random disorder in higher dimensions. We clearly demonstrate localization by investigating transport properties, spatial and momentum distributions. Since the interaction in the BEC can be controlled, this system represents a novel tool to solve fundamental questions on the interplay of disorder and interaction and to explore exotic quantum phases.

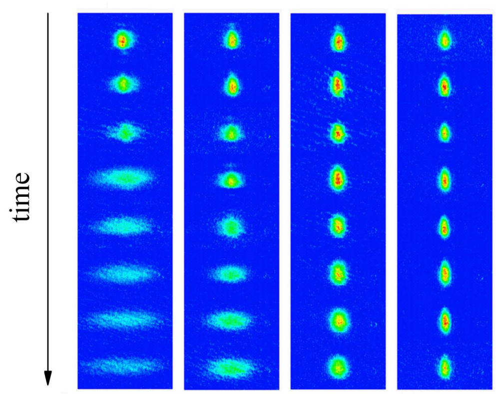

Figure 1: *Images of the BEC expanding in the bichromatic lattice for different ratios between disorder amplitude Δ and tunnelling energy J. The crossover between ballistic expansion and localization is clearly shown.*

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Ultracold Physics at UConn, Including Spectra of Ultracold Molecules

W. C. Stwalley

Department of Physics, University of Connecticut, U-3046, Storrs, CT 06269, USA

The Physics Department at UConn includes seven faculty involved (often collaboratively) in a wide variety of ultracold physics projects. I will briefly survey a sample of these projects and then focus on recent developments of techniques for studying the electronic spectroscopy of ultracold molecules formed by photoassociation of ultracold atoms. In particular, this work, pioneered in our lab by Dr. Dajun Wang and carried out in collaboration with Professors Ed Eyler and Phil Gould, has focused on demonstrations of high resolution multiple resonance spectroscopy for highly vibrationally excited levels of the $X^1\Sigma^+$ state and the $a^3\Sigma^+$ state of $^{39}K^{85}Rb$. Such demonstrations show the power and sensitivity of such techniques for studying states with exotic potential curves at intermediate and large internuclear distances, for determining rotational and hyperfine structure of such vibrational levels, and for precisely defining binding energies of such high levels.

From the hot big bang to the coldest temperatures ever achieved

W. Ketterle

MIT-Harvard Center for Ultracold Atoms, and Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139-4307, USA

This talk is a journey from the big bang to the lowest temperatures ever achieved. After an introduction into the concept of temperature, our journey takes us from the earth to the sun and to temperatures of a trillion Kelvin, which are generated in heavy ion collisions and simulate conditions ten millionths of a second after the big bang. The lowest temperatures are a trillion times colder than room temperature and provide new insight into superfluidity and other forms of ice-cold matter.

Disorder-Induced Localization in a Bose-Einstein Condensate

D. Dries[1], S. E. Pollack[1], Y. P. Chen[2], J. Hitchcock[1], T. Corcovilos[1], R. G. Hulet[1]

[1]*Department of Physics and Astronomy, Rice University, Houston, TX 77005, USA*
[2]*Department of Physics, Purdue University, West Lafayette, IN 47907, USA*

Random disorder is known to play an important role in the electrical properties of conductors and superconductors. In those materials, disorder may be caused by crystal defects, impurities, or anything else that changes the landscape of how electrons move in a material. If the disorder is sufficiently strong to localize the electrons the material undergoes a transition to an insulating state, as has been observed in thin-film and granular superconductors. A complete understanding of the transition and the nature of the insulating state remain elusive due to the limitations imposed by the complexity of actual materials. Atomic Bose-Einstein condensates (BECs) afford the opportunity to explore the role of disorder in superfluids where the physical parameters are well characterized, and moreover, can be varied. The interplay of disorder and interactions is of particular interest, because weakly interacting disordered systems can undergo a quantum phase transition to the Anderson localized state.

We have studied the transport and phase coherence properties of a ^{7}Li BEC in the presence of disorder produced by optical speckle[1]. At moderate disorder strengths, V_d, we observe inhibited transport and damping of dipole oscillations. Contrary to previous expectations, in-situ density measurements reveal only small density modulations in this regime. Time-of-flight images exhibit random but reproducible interference. Only at much higher V_d does the condensate fragment into many quasi-independent pockets, which is accompanied by a reduction of interference contrast. These measurements show that while transport of the condensate is inhibited at moderate V_d, the condensate remains connected and phase coherent.

Anderson localization, recently observed in atomic BECs[2,3], arises from single particle interference which requires that atomic interactions be sufficiently weak that the condensate healing length is larger than the disorder length scale. ^{7}Li is an interesting atom for these studies because the scattering length, a, can be readily varied via a Feshbach resonance. Of particular interest is the ability to tune a close to and through zero[4], providing a systematic way of varying the healing length. We are using this zero-crossing to investigate the role of weak interactions, both repulsive and attractive, in the presence of disorder.

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A purely dipolar quantum gas

Tilman Pfau

5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, D-70550 Stuttgart, Germany, t.pfau@physik.uni-stuttgart.de

In usual experiments with BECs, the only relevant interaction is the isotropic and short-range contact interaction, which is described by a single parameter, the scattering length a. In contrast, the dipole–dipole interaction between particles possessing an electric or magnetic dipole moment is of long range character and anisotropic, which gives rise to new phenomena [1].

Most prominently, the stability of a dipolar BEC depends not only on the value of the scattering length a, but also strongly on the geometry of the external trapping potential. Here, we report on the experimental investigation of the stability of a dipolar BEC of ^{52}Cr as a function of the scattering length and the trap aspect ratio. We find good agreement with a universal stability threshold arising from a simple theoretical model. Using a pancake-shaped trap with the dipoles oriented along the short axis of the trap, we are able to tune the scattering length to zero, stabilizing a purely dipolar quantum gas [2].

We also experimentally investigated the collapse dynamics of a dipolar condensate of ^{52}Cr atoms when the s-wave scattering length characterizing the contact interaction is reduced below a critical value. A complex dynamics, involving an anisotropic, d-wave symmetric explosion of the condensate, was observed on time scales significantly shorter than the trap period. At the same time, the condensate atom number decreases abruptly during the collapse. We compare our experimental results with numerical simulations of the three-dimensional Gross-Pitaevskii equation, including the contact and dipolar interactions as well as three-body losses (see Fig.1). The simulations indicate that the collapse is accompanied by the formation of two vortex rings with opposite circulations.[3].

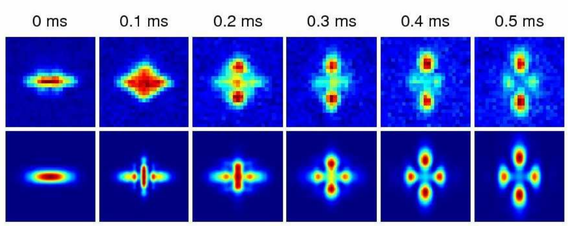

Figure 1: *Dipolar collapse dynamics for different hold times in the trap. Upper line: experiment, lower line: theory.*

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1D Bose gases

David Weiss

Department of Physics, Penn State, PA 16802, USA

I will describe a series of experiments with 1D Bose gases. Several equilibrium properties of these gases have been measured across coupling limits, including the strongly coupled or Tonks-Girardeau limit. These include energies, cloud lengths and pair correlations. There is good agreement with the well-known, exact Lieb-Liniger solutions for a δ-function interacting Bose gas. These gases are integrable many-body systems, so they have the unique property that they do not come to conventional thermodynamic equilibrium. This has also been demonstrated in the lab. How thermalization begins when integrability starts to be lifted is an open question in quantum mechanics. We are trying to address this question experimentally. I will describe that work and discuss a theoretical model of a particular thermalization mechanism.

I will also give an update on our progress toward building a neutral atom quantum computer in a site-addressable 3D optical lattice.

Work performed in collaboration with Jean-Felix Riou, Toshiya Kinoshita and Trevor Wenger at Penn State and Vladimir Yurovsky from the Chemistry Department of Tel Aviv University.

Fermi Gases with Tunable Interactions

J. E. Thomas

Physics Department, Duke University, Durham, NC 27708-0305

Optically-trapped mixtures of spin 1/2-up and spin 1/2-down Fermi atoms are a new paradigm for exploring interacting Fermi systems in nature. Even though it is dilute, a Fermi gas tuned near a Feshbach resonance is currently the most strongly interacting nonrelativistic system known, enabling tests of nonperturbative many-body theories in disciplines from high temperature superconductors to nuclear matter. Our studies of universal thermodynamics and quantum viscosity reveal nearly perfect fluidity, of great interest in the quark-gluon plasma and string theory communities. In the weakly interacting regime, we observe anomalous spin waves in coherently prepared clouds.

Photoemission Spectroscopy for Ultracold Atoms

D. S. Jin

JILA - University of Colorado, Boulder, CO 80309, USA

We perform momentum-resolved rf spectroscopy on a Fermi gas of ^{40}K atoms in the region of the BCS-BEC crossover. This measurement is analogous to photoemission spectroscopy, which has proven to be a powerful probe of excitation gaps in superconductors. We measure the single-particle spectral function, which is a fundamental property of a strongly interacting system and is directly predicted by many-body theories. For a strongly interacting Fermi gas near the transition temperature for the superfluid state, we find evidence for a large pairing gap.

Universality in Strongly Interacting Fermi Gases

P. D. Drummond[1], H. Hu[1,2], X-J. Liu[1]

[1]*ARC Centre of Excellence for Quantum-Atom Optics, Department of Physics, University of Queensland, Brisbane, Queensland 4072, Australia*
[2]*Department of Physics, Renmin University of China, Beijing 100872, China*

The theory of strongly interacting fermions is of great interest. Interacting fermions are involved in some of the most important unanswered questions in condensed matter physics, nuclear physics, astrophysics and cosmology. Though weakly-interacting fermions are well understood, new approaches are required to treat strong interactions. In these cases, one encounters a "strongly correlated" picture which occurs in many fundamental systems ranging from strongly interacting electrons to quarks.

The main theoretical difficulty lies in the absence of any small coupling parameter in the strongly interacting regime, which is crucial for estimating the errors of approximate approaches. Although there are numerous efforts to develop strong-coupling perturbation theories of interacting fermions, notably the many-body T-matrix fluctuation theories their accuracy is not well-understood. Quantum Monte Carlo (QMC) simulations are also less helpful than one would like, due to the sign problem for fermions or, in the case of lattice calculations, the need for extrapolation to the zero filling factor limit.

Recent developments in ultracold atomic Fermi gases near a Feshbach resonance with widely tunable interaction strength, densities, and temperatures have provided a unique opportunity to quantitatively test different strong-coupling theories. In these systems, when tuned to have an infinite s-wave scattering length - the unitarity limit - a simple universal thermodynamic behavior emerges [1]. Due to the pioneering efforts of many experimentalists, the accuracy of thermodynamic measurements at unitarity has improved significantly. A breakthrough occurred in early 2007, when both energy and entropy in trapped Fermi gases were measured without invoking any specific theoretical model [2]. This milestone experiment, arguably the most accurate measurement in cold atoms, has an accuracy at the level of a few percent.

We give an overview of the current experimental and theoretical situation, including detailed quantitative comparisons of theory and several different experiments that establish the first evidence for universality. We also explore the extension of these theories to new regimes, including the exactly soluble one-dimensional regime, where the FFLO or modulated superfluid phase can form in the case of a polarized Fermi gas, and possible regimes with more than two types of interacting fermion. Finally, we explore the open question of how to distinguish between existing theories of strongly interacting Fermi gases.

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[2]L. Luo *et al*., Phys. Rev. Lett. **98**, 080402 (2007).

Coherent control of pairs of atoms in a double-well optical lattice.

J. V. Porto

Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, Gaithersburg, Maryland, 20899, USA

I will describe a novel double-well optical lattice and several experiments where we control the vibrational and internal states of pairs of ^{87}Rb trapped in the lattice, including controlled pairwise interactions useful for quantum logic. The lattice is generated from a single, retro-reflected laser beam that is folded onto itself such that the beam passes through the origin four times[1]. The resulting four-beam, 2D optical lattice is phase stable, and by changing the input polarization the unit cell can be changed continuously from a single-site configuration to a double-well configuration. This lattice has several interesting properties: the lattice potential is two-dimensional, and is not separable in the x and y directions; and spatially varying polarization gradients (combined with the vector light shift of ^{87}Rb) give rise to site- and spin-dependent light shifts, resulting in two inter-penetrating sub-lattices of 'left' and 'right' sites with two different effective magnetic fields in the two sub-lattices.

Using this lattice, we have loaded and measured number-squeezed and Poisson states of atoms in the individual sites of the lattice[2] and demonstrated dynamic control of the motional state of atoms, adiabatically transferring atom population between adjacent sites of the lattice as well as between different energy bands[3]. The local effective field gradient allows us to spectroscopically resolve atoms in the two sub-lattices (separated by 400 nm), and we have demonstrated independent control of the atom spins in the separate sub-lattices[4]. Finally, combining these techniques, we demonstrate controlled spin-dependent exchange interactions of atoms that have been merged into the same well[5]. The observed exchange oscillations represent the essential component of an entangling $\sqrt{\mathrm{SWAP}}$ gate.

I will briefly discuss these experiments and our current work using coherent control of atoms in hyperfine clock states with long coherence times.

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Minimum instances of topological matter in an optical plaquette

Belén Paredes

Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany

Topological matter is an unconventional form of matter [1]: it exhibits a global hidden order which is not associated to the spontaneous breaking of any symmetry. The defects of this exotic type of order are anyons, quasiparticles that exhibit fractional statistics. Except for the fractional quantum Hall effect, there is no experimental evidence as to the existence of topologically ordered phases. It remains a huge challenge to develop theoretical techniques to look for topological liquids in realistic models and find them in the laboratory. In this direction, artificial design of topological states in the versatile and highly controllable atomic systems in optical lattices appears to be a very promising possibility [2].

In this talk I will show how to use ultracold atoms in optical lattices to create and detect different instances of topological order in the minimum non-trivial lattice system: four spins in a plaquette. Using a superlattice structure [3] it is possible to devise an array of disconnected plaquettes [4], which can be controlled and detected in parallel. When the hopping amplitude between plaquette sites is very small, atoms are site localized and the physics is governed by the remaining spins. By combining different techniques I will show how to prepare these spins in minimum versions of topical topological liquids: a Resonating Valence Bond state, a Laughlin state, and a string-net condensed state. By locally addressing each spin in a plaquette, I will show how to create anyonic excitations on top of these liquids and detect their fractional statistics. In addition, I will propose a way to design a plaquette four-spin interaction, the building block Hamiltonian of a lattice topological theory.

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Atom interferometry with a weakly interacting Bose-Einstein condensate

G. Modugno

LENS and Dipartimento di Fisica, Università di Firenze, Italy

Bose-Einstein condensates have been considered since long the most appropriate source for interferometry with matter waves, due to their maximal coherence properties. However, the realization of practical interferometers with condensates has been so far hindered by the presence of the natural atom-atom interaction, which dramatically affects their performance. We will report on the realization of an interferometer based on a Bose-Einstein condensate of ^{39}K atoms, where the contact interaction between atoms can be tuned by means of a Feshbach resonance [1]. We observe that the coherence time of the interferometer is greatly enhanced by a reduction of the contact interaction by orders of magnitude from the standard value[2]. We also study the effect of the residual magnetic dipole-dipole interaction.

Our results indicate that interferometry with well suited Bose-Einstein condensates is possible, with an expected gain in performances. Our specific interferometer, which is based on Bloch oscillations in an optical lattice under gravity, features a high spatial resolution that is promising for future application to the measurement of fundamental forces in proximity of surfaces.

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Formation of cold molecules or/and laser cooling of molecules

P. Pillet

Laboratoire Aimé Cotton, CNRS, Univ Paris-Sud, Bât. 505, 91405 Orsay, France

The field of cold molecules has been opened in 1998 with the demonstration producing cold samples of ground-state of dimers of cesium in the microkelvin temperature range, via photoassociation of cold atoms. This result has been quickly followed by the elaboration of various methods to prepare cold molecules in the kelvin or millikevin temperature range, by starting with molecules, such as cryogenically cooled buffer gas, slow down of supersonic beam, billiardlike collisions, spinning rotor, velocity filtering of an effusive beam. Until now, cold molecules in the micro-range can only been achieved starting with cold atoms. The methods of producing cold molecules from cold atoms (via photoassociation or through magneto-association), however, lead to the production of vibrational excited molecules. For additional applications, the challenge is in the preparation and the control of molecules in the ground vibrational and rotational state.

The vibrational cooling through optical pumping using a shaped broadband femtosecond laser has been demonstrated for Cs_2 molecules. The molecules initially formed via photoassociation of cold cesium atoms are in several vibrational levels, v, of the singlet ground state. The broadband femtosecond laser can electronically excite the molecules, leading via a few absorption - spontaneous emission cycles, to a redistribution of the vibrational population in the ground state. By removing the laser frequencies corresponding to the excitation of the v=0 level, we realize a dark state for the so-shaped femtosecond laser, yielding with the successive laser pulses to an accumulation of the molecules in the v=0 level. The mechanism can be called Molecular Incoherent Vibrationally Selective Population Trapping in analogy to the mechanism of Velocity Selective Coherent Population Trapping (VSCPT) in atoms for sub-recoil cooling. The method opens novel perspectives for vibrational and rotational cooling, and for the laser manipulation of molecules.

Ultracold halo dimers and few-body physics

R. Grimm[a,b]

[a] *Institut für Experimentalphysik, Universität Innsbruck, Innsbruck, Austria*
[b] *Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, Innsbruck, Austria*

Ultracold dimers in s-wave states are in the quantum halo regime[1], if their binding energy is much smaller than a typical energy set by the long-range van der Waals interaction. In this regime, the scattering length is very large and details of the interatomic interaction become irrelevant. Studying the interactions of halo dimers provides experimental access to universal phenomena in few-body physics[2].

We create halo dimers of identical bosons by Feshbach association in an ultracold gas of cesium atoms. In a trapped ultracold atom-dimer mixture we study inelastic atom-dimer scattering[3]. Our main result is an atom-dimer scattering resonance, which we interpret as result of a trimer state hitting the atom-dimer threshold. This phenomenon can be interpreted in terms of Efimov's scenario and provides new information on Efimov states which complements previous work on three-body recombination in an atomic gas[4].

Further experiments on dimer-dimer interactions[5] are based on a pure trapped sample of Cs_2 halo dimers. We measure the relaxation rate coefficient for decay to lower-lying molecular states and study the dependence on scattering length and temperature. We identify a pronounced loss minimum with varying scattering length along with a further suppression of loss with decreasing temperature. These observations provide insight into the physics of a few-body quantum system that consists of four identical bosons at large values of the two-body scattering length.

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Strong Dissipation Inhibits Losses and Induces Correlations in Cold Molecular Gases

S. Dürr[1] , N. Syassen[1], D. M. Bauer[1], M. Lettner[1], T. Volz[1], D. Dietze[1], J. J. García-Ripoll[1,2], J. I. Cirac[1], G. Rempe[1]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, Garching, Germany*
[2]*Universidad Complutense, Facultad de Físicas, Ciudad Universitaria s/n, Madrid, Spain*

Atomic quantum gases in the strong–correlation regime offer unique possibilities to explore a variety of many–body quantum phenomena. Reaching this regime has usually required both strong elastic and weak inelastic interactions, as the latter produce losses. We show that strong inelastic collisions can actually inhibit particle losses and drive a system into a strongly–correlated regime. Studying the dynamics of ultracold molecules in an optical lattice confined to one dimension, we show that the particle loss rate is reduced by a factor of 10. Adding a lattice along the one dimension increases the reduction to a factor of 2000. Our results open up the possibility to observe exotic quantum many–body phenomena with systems that suffer from strong inelastic collisions.[1]

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Quantum Universality in Few-Body Systems

C. Chin

Physics Department and James Franck Institute, University of Chicago

We discuss prospects to investigate universality in few-body systems derived from bosonic and fermionic atoms in the quantum threshold regime. In particular, we describe new spectroscopic tools to identify and explore the universality of quantum systems with a designated number of ultracold atoms, ratcheting our comprehension from a single atom to many. Universality has been well established in the two- and many-body regimes, describing the physics of these systems solely by the two-body scattering length; it is unclear, however, how universality persists in the intermediate few-body regime. Among other directions, I propose a novel interferometric detection of two- and three-body interactions by probing the evolution of quantum superpositions of atomic occupancies in optical lattice sites. Possible limitations on the technique, and remedies based on precision control of atoms in the internal and external degrees of freedom will be discussed.

Number squeezing and entanglement in a Bose Einstein condensate

J. Esteve, C. Groß, A. Weller, T. Zibold, S. Giovanazzi, M. K. Oberthaler

Kirchhoff Institut für Physik, Heidelberg, Germany

We report on our recent experimental results obtained with a new very stable double well setup combined with high spatial resolution imaging. The new setup allows the first direct demonstration of relative number squeezed states at finite temperature. With in situ imaging the statistics of the atom number difference between left and right is analyzed directly and reveals the expected deviation from the classical shot noise limit. The observation of the corresponding fluctuation of the relative phase allows the experimental demonstrate that a number squeezed state is produced which improves the performance of a standard Ramsey type interferometer beating the standard quantum limit by a factor of two [1]. Furthermore, with the observed squeezing a sufficient criterion for pairwise entanglement can be constructed confirming that for our experimental parameters pairwise entanglement between the atoms exist even at finite temperature [2,3,4].

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Mapping the phase diagram of a two-component Fermi gas with strong interactions

Y. Shin , C. H. Schunck, A. Schirotzek, W. Ketterle

MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, and Department of Physics, MIT, Cambridge, MA 02139, USA

The pairing of fermions is the underlying mechanism for superconductivity and superfluidity. Ultracold atomic Fermi gases present a highly controllable model system for studying interacting Fermi mixtures. Tunable interactions and the control of population among the spin components provide unique opportunities to investigate the stability of fermion pairs and possibly to search for exotic forms of superfluidity. In this talk, we present the phase diagram of a two-component Fermi gas of ^{6}Li atoms with strong interactions[1]. Using tomographic techniques, we determine the spatial structure of a trapped Fermi mixture, mapping out the superfluid phase versus temperature, density imbalance, and interaction strength. At low temperature, the sample shows spatial discontinuities in the spin polarization. This is the signature of a first-order superfluid-to-normal phase transition, which disappears at a tricritical point where the nature of the phase transition changes from first-order to second-order. At zero temperature, there is a quantum phase transition from a fully-paired superfluid to a partially-polarized normal gas. The critical polarization of the normal gas increases with stronger coupling strength and eventually, the partially-polarized normal phase disappears at a critical interaction strength, above which all minority atoms pair with majority atoms. The microscopic properties of the fermion pairs are studied with rf spectroscopy[2].

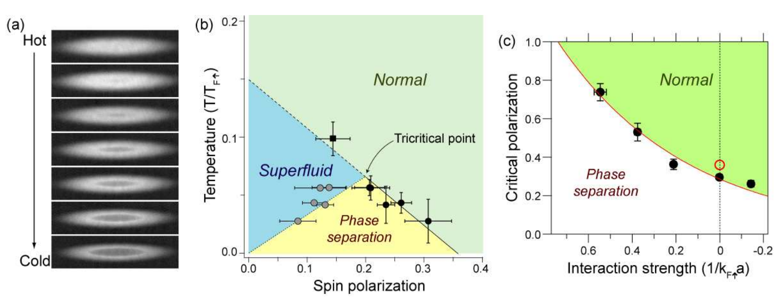

Figure 1: *(a) Phase transition in a trapped Fermi mixture. in situ distribution of column density difference for various temperatures. Phase diagram (b) with resonant interactions and (c) in the plane of interaction strength and spin polarization.*

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Towards Quantum Magnetism with Ultracold Quantum Gases in Optical Lattices

I. Bloch

Institut für Physik, Johannes Gutenberg-University, 55099 Mainz, Germany

Quantum mechanical superexchange interactions form the basis of quantum magnetism in strongly correlated electronic media and are believed to play a major role in high-Tc superconducting materials. We report on the first direct measurement of such superexchange interactions with ultracold atoms in optical lattices. After preparing a spin-mixture of ultracold atoms with the help of optical superlattices in an antiferromagnetically ordered state, we are able to observe a coherent superexchange mediated spin dynamics down to coupling energies as low as 5 Hz. Furthermore, it is shown how these superexchange interactions can be fully controlled in magnitude and sign. The prospects of using such superexchange interactions for the investigation of dynamical behaviour in quantum spin systems and for quantum information processing will be outlined in the talk. In addition results on strongly interacting Fermi-Fermi mixtures in optical lattices are presented. We probe the degenerate fermionic quantum gases with initial temperatures as low as $T/T_F = 0.13$ by both measuring local and global observables of the system and by comparing these measurements to 3D numerical Dynamical Mean Field Theory (DMFT) calculations for the case of repulsive interactions. We furthermore discuss the case of strong attractive interactions, where the fermionic quantum gas has converted into a gas of strongly bound pairs, whose behaviour can be mapped onto a quantum spin model.

Circuit QED: Recent Results in Quantum Optics with Superconducting Circuits

Robert Schoelkopf

Departments of Applied Physics and Physics, Yale University, New Haven CT, USA

Circuit QED[1] is an approach for studying quantum optics in a superconducting integrated circuit. By combining a one-dimensional transmission-line cavity that stores microwave photons and a superconducting qubit that plays the role of an artificial atom, one can easily enter the strong coupling limit of cavity QED. In recent experiments, we attain couplings that are several percent of the qubit or cavity frequency, and in fact approach the maximal fine-structure limit for a electric-dipole interaction of light and matter, giving rise to a remarkable vacuum Rabi splitting of several hundred linewidths. We will present studies of the nonlinear response of this system, which shows two novel effects: 1) each vacuum Rabi peak develops a supersplitting, which can be understood in a simple picture as the saturation of a new two-level system consisting of photon-qubit superpositions, and 2) the emergence of additional peaks, corresponding to multi-photon transitions up the Jaynes-Cummings ladder, and constituting a simple demonstration of the $\sqrt{n}$ nonlinearity in this system. Experiments show striking agreement with analytical and numerical predictions confirming the Jaynes-Cummings Hamiltonian description of the system. The coherent coupling of qubits to microwave photons that are guided around a chip by wires raises many possibilities for quantum information and communication. I will also review experiments demonstrating the generation of single 5 GHz photons on demand, and the communication of quantum information between qubits using photons in a cavity as an intermediary.

Work performed in collaboration with S.M. Girvin, M.H. Devoret, Lev S. Bishop, A. Blais, J.M. Chow, L. Frunzio, J.M. Gambetta, A.A. Houck, B.R. Johnson, Jens Koch, J. Majer, J.A. Schreier, D.I. Schuster, E. Thuneberg, and A. Wallraff.

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Dispersively coupled optomechanical systems: a new approach to quantum optics with radiation pressure

J. G. E. Harris

Departments of Physics and Applied Physics, Yale University, New Haven, USA

Radiation pressure provides a unitary coupling between the electromagnetic field and the center-of-mass motion of macroscopic objects. In principle it should be possible to use this coupling to imprint the electromagnetic field's quantum fluctuations onto objects which, due to their large size and high temperature, would otherwise behave classically. Although this is a fascinating goal and progress in the past few years has been rapid, the technical challenges are considerable. In practice one must build a high finesse optical cavity which is coupled to an ultrasensitivie mechanical force sensor. The twin requirement of a delicate mechanical force detector and a high finesse cavity has proved to be a major barrier to observing quantum effects in optomechanical systems.

In my talk I will describe an optomechanical device in which a 50 nm-thick dielectric membrane is placed at the waist of a high-finesse optical cavity. In this ”membrane-in-the-middle” geometry, the coupling between the cavity mode and the membrane is closely analogous to the dispersive coupling between a cavity mode and an off-resonant atom. We demonstrate that even with the dielectric membrane inside the cavity it is possible to achieve a cavity finesse equal to 150,000. We also find that some membranes have a surprisingly large mechanical quality factor: $Q = 1,000,000(10,000,000)$ at a bath temepratures $T = 300$ K (0.3 K), leading to a near-world-record force sensitivity of 10^{-15} N/Hz$^{1/2}$ (10^{-17} N/Hz$^{1/2}$).

This combination of high finesse and high mechanical Q allows us to laser cool the 100 kHz vibrational mode of the membrane. Starting at room temperature, we achieve a laser-cooled temperature of 7 mK. Straighforward estimates indicate that if this device is placed in a cryostat at 0.3 K, the same cooling should bring the membrane to its quantum mechanical ground state.

I will also describe how the dispersive coupling in this device allows us to realize a novel type of readout in which light leaving the cavity only carries information about the square of the membrane's position. Such a ”position-squared” measurement has long been known to be a key requirement for making a phonon-resolving quantum nondemolition measurement of a mechanical oscillator. I will review the prospects for realizing such a measurement and observing real-time quantum jumps of a micromechanical device. Although challenging, it appears this goal could be reached using present-day technology.

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Cavity Optomechanics: Backaction Cooling of Mechanical Oscillators

A. Schliesser, O. Arcizet, R. Rivière, G. Anetsberger, T. J. Kippenberg

Max Planck Institut für Quantenoptik, Garching, Germany

The possibility to observe quantum phenomena of macroscopic objects has been a long-standing challenge in Quantum Physics and has recently received significant attention as researchers from diverse communities seek to demonstrate quantum phenomena of nano- and micro-scale mechanical oscillators coupled to optical laser fields. A major challenge, in this new field of *Cavity Optomechanics*[1] are the extremely low temperatures required to cool mechanical systems down to their ground state as well to perform quantum limited measurements of the mechanical amplitudes in the regime of low occupancy. In this talk I will describe the advances the Max Planck Institute of Quantum Optics has made in this field. Using on chip micro-cavities that combine both optical and mechanical degrees of freedom in one and the same device, we have been able to shown that the radiation pressure back-action of photons can be used to passively cool the mechanical oscillator[2], akin to Doppler Cooling of Atoms. Furthermore, we have been able to demonstrate for the first time resolved sideband cooling[3] [4], by using optical microresonators whose mechanical oscillator frequency exceeds the cavity decay rate. This technique is well known in Atomic Physics to provide ground state cooling. Moreover the ability to monitor the motion of the oscillator with a quantum limited sensitivity of $10^{-18} m/\sqrt{Hz}$ will be discussed and a description of our quest to ever lower phonon occupancies using cryogenic exchange gas cooling to 1.6 K described.

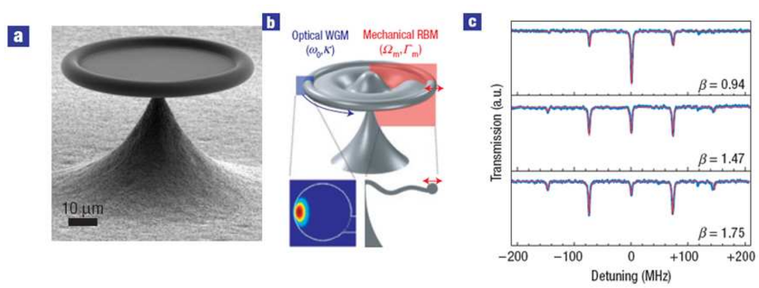

Figure 1: *Radiation pressure cooling of toroidal microcavities in the resolved sideband regime*[2,4].

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Exciton-polariton condensation in semiconductor microcavities

Y. Yamamoto[a,b,*] , S. Utsunomiya[b], H. Deng[a], C.-W. Lai[a], G. Roumpos[a], A. Löffler[c], S. Höfling[c], A. Forchel[c]

[a]*Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4085,USA*
[b]*National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo101-8430, Japan*
[c]*Technische Physik, Universität Würzburg, Am Hubland, 97074 Würzburg, Gernmay*
[*]*yosihisa@stanford.edu*

An experimental technique of controlling spontaneous emission of an atom by use of a cavity is referred to as cavity quantum electrodynamics and has been extensively studied for atoms [1] and excitons [2]. Due to a strong collective dipole coupling between microcavity photon fields and QW excitons, a semiconductor planar microcavity features a reversible spontaneous emission or normal mode splitting into upper and lower branches of exciton-polaritons [3]. A metastable state of lower polariton at zero in-plane momentum (k=0) has emerged as a new candidate for observation of Bose-Einstein condensation (BEC) in solids [4]. An exciton-polariton has an effective mass of four orders of magnitude lighter than an exciton mass, so the critical temperature for polariton BEC is four orders of magnitude higher than that for exciton BEC at the same particle density. An exciton-polariton can easily extend a phase coherent wavefunction in space through its photonic component in spite of crystal defects and disorders, which is known as a serious enemy to exciton BEC.

In this talk we will discuss the recent progress on the dynamic condensation of exciton-polaritons and the application to quantum emulation of many body physics. Quantum degeneracy at thermal equilibrium condition was achieved by using a device structure with multiple quantum wells and a blue detuning regime [5]. The formation of a first order coherence (off-diagonal long range order) was confirmed by the Young’s double slit interferometer [6] and the bosonic final state stimulation (photon bunching effect) was observed by the Hanbury-Brown and Twiss interferometer [7]. The spontaneous spin polarization was confirmed at condensation threshold [8], and the Bogoliubov excitation spectrum was observed above threshold [9]. Finally the Bose-Hubbard model was implemented in a one-dimensional array of polariton condensates, in which the competition between a superfluid zero state and pi state was observed [10].

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The frontiers of attosecond physics

G. Doumy, P. Colosimo, J. Wheeler, R. Chirla, A. M. March, P. Agostini, L. F. DiMauro

Department of Physics, The Ohio State University, Columbus, OH 43210, USA

The genesis of light pulses with attosecond (10^{-18} seconds) durations signifies a new frontier in time-resolved physics. The scientific importance is obvious: the time-scale necessary for probing the motion of an electron(s) in the ground state is attoseconds (atomic unit of time = 24 *as*). The availability of attosecond pulses would allow, for the first time, the study of the time-dependent dynamics of correlated electron systems by freezing the electronic motion, in essence exploring the structure with ultra-fast snapshots, then following the subsequent evolution using pump-probe techniques.

This talk will examine the fundamental principles of attosecond formation by Fourier synthesis of a high harmonic comb and phase measurements using two-color techniques. Quantum control of the spectral phase, critical to attosecond formation, has its origin in the fundamental response of an atom to an intense electromagnetic field. We will interpret the laser-atom interaction using a semi-classical trajectory model. Finally, the comparison of recent measurements with the predictions of strong-field scaling will be used to show that high energy photons with inherently shorter bursts can be created using long wavelength fundamental fields.

Strong field control of x-ray processes

L. Young[1] , R. W. Dunford[1], E. P. Kanter[1], B. Krässig[1], S. H. Southworth[1], R. Santra[1,2]

[1]*Argonne National Laboratory, Argonne, IL 60439, USA*
[2]*Department of Physics, University of Chicago, Chicago, IL 60637, USA*

Control of x-ray processes using intense optical lasers represents an emerging scientific frontier—one which combines x-ray physics with strong-field laser control. While the past decade has produced many examples where phase and amplitude controlled lasers at optical wavelengths are used to manipulate molecular motions, the extension to control of ultrafast, intraatomic, inner-shell processes is quite new. Gas phase systems are particularly suitable for illustrating the basic principles underlying combined x-ray and laser interactions. We will discuss three scenarios by which strong electromagnetic fields can be used to modify resonant x-ray absorption in a controlled manner: (1) Ultrafast-field ionization of atoms[1] at laser intensities in the range 10^{14}–10^{15} W/cm^2; (2) modification of electronic structure of inner-shell-excited systems by laser dressing[2] at 10^{12}–10^{13} W/cm^2; and (3) control of resonant x-ray absorption by molecules through laser-induced spatial alignment[3] at 10^{11}–10^{12} W/cm^2. The x-ray microprobe methodology developed for these demonstrations can be applied to ultrafast imaging of laser-controlled molecular motions and Ångstrom-level structural imaging of biomolecules without the need for crystallization.

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Probing Atomic Wavefunctions via Strong Field Light-Matter Interaction

D. Shafir[1], Y. Mairesse[2,3], D. M. Villeneuve[3], P. B. Corkum[3], N. Dudovich[1,3]

[1]*Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel*
[2]*CELIA, Université Bordeaux I, UMR 5107 (CNRS, Bordeaux 1, CEA), 351 Cours de la Libération, 33405 Talence Cedex, France*
[3]*National Research Council of Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6, Canada*

I will present an approach to perform correlated measurements of electronic wavefunctions and will describe how the correlated properties of the measurement can be applied to probe atomic states. The approach relies on the manipulation of an electron ion recollision process in a strong laser field [1]. We apply a two color field to direct the free electron's motion during one optical cycle (see Fig. 1A). Manipulating a recollision process allows us to resolve the symmetry of the atomic wavefunction with notably high contrast (see Fig. 1B).

The measurement, dictated by the strong laser field, provides a direct insight into its interaction with the atom. This approach will have an important impact on molecular tomography [2] and extend it to more complex molecular orbitals. Since the method is closely related with attosecond technology, time and space will combine in the future allowing dynamic imaging of a broad range of atomic and molecular processes.

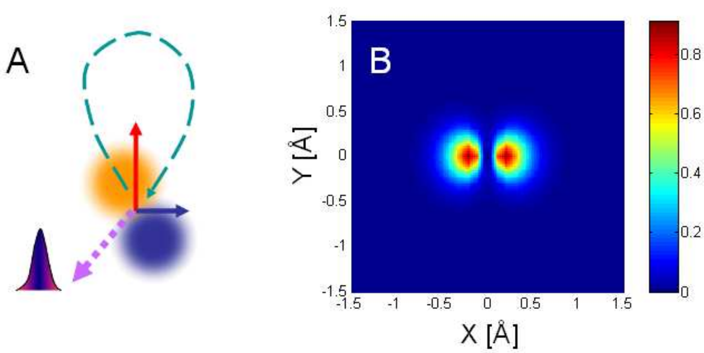

Figure 1: *A. Schematic drawing of attosecond pulse generation with a two color field. The motion of the electron is schematically described by the blue dashed line. The recollision projects the ground state into the optical frequencies of the emitted pulse. B. Retrieved Neon mixed $2p$ orbital.*

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Poster Session I

Monday, July 28
4:15 pm – 6:00 pm
Wilbur Cross Building, Reading Rooms

Atomic and Ionic Structure

Spectroscopy

Atomic Clocks

Atoms in External Fields

Optical Lattices

Quantum Information

Quantum Optics & Cavity QED

Multi-configuration Dirac-Fock Calculations for Atomic Structures of Ca^+

Shao-Hao Chen[1], Bo Qing[1], Xiang Gao[2], Jia-Ming Li[1,2]

[1]*Key Laboratory of Atomic and Molecular Nanosciences of Education Ministry, Department of Physics, Tsinghua University, Beijing 100084, China*
[2]*Department of Physics, Shanghai Jiaotong University, Shanghai 200240, China*

The metastable $3d\,^2D_{3/2,5/2}$ states of Ca^+ are interesting in various experimental fields such as optical frequency standards[1], quantum information science[2], and astrophysics[3]. Ca^+ is also a challenging system for the calculations of atomic structure, due to the effects of d orbitals and strong core-valence correlation effects[4]. Recently, a lot of experimental[5,6] and theoretical[5,7] research works have been done for the lifetimes of $3d\,^2D_{3/2,5/2}$ states of Ca^+.

In this letter, we calculated the $3d\,^2D_{3/2,5/2}$ and $4p\,^2P_{1/2,3/2}$ energy levels of Ca^+, using multi-configuration Dirac-Fock (MCDF) method with the Breit interactions and quantum electrodynamics corrections. Based on multi-configuration self-consistent field (MCSCF) calculation strategies[8], we optimized a set of high-quality orbital basis. Owing to the feature of d orbital in Ca^+, the obitals with approximate equal effective quantum number $\nu = n - \mu$ are defined as a layer, e.g. $4s$, $3d$ and $4p$ constitute the $\nu = 2$ layer. In order to consider the core-valence correlation, the configurations created by single excitations respectively from core $3p^6$ and valence $4s^1$ are included. In order to consider the monopole, dipole and quadrupole excitation correlations uniformly, the $4f$ and $5g$ orbitals are included when optimizing the $\nu = 2$ layer. Then the obital basis is extended by single configuration optimization to $\nu = 7$ layer. The configurations created by single excitation from deeper core $3s^2$ are also included in the configuration interaction calculations. Finally, we obtained a uniform convergence for the energy levels. The percentage differences between our calculated energy levels and available experimental results are approximate 1% for $^2D_{3/2,5/2}$ and 0.1% for $^2P_{1/2,3/2}$.

It is anticipated that all of the E1, E2 and M1 radiation transition rates between the states of $^2S_{1/2}$, $^2D_{3/2,5/2}$ and $^2P_{1/2,3/2}$, as well as the lifetimes of $^2D_{3/2,5/2}$ and $^2P_{1/2,3/2}$ states, can be calculated in high precision based on the MCSCF calculation strategies presented in this letter.

Reference

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Isotope shift in the electron affinity of sulfur: observation and theory

M. Godefroid[1], T. Carette[1], C. Drag[2], C. Blondel[2], C. Delsart[2], C. Froese Fischer[3], O. Scharf[1]

[1]*Service de Chimie Quantique et Photophysique, Université Libre de Bruxelles B 1050 Brussels, Belgium*
[2]*Laboratoire Aimé-Cotton, CNRS, Université Paris-sud, F-91405 ORSAY cedex, France*
[3]*Department of Electrical Engineering and Computer Science, Box 1679B, Vanderbilt University, Nashville TN 37235, USA*

Photodetachment microscopy[1] was performed on a beam of S^- generated by a hot cathode discharge in a mixture of 98% Ar and 2% CS_2, with the sulfur isotopes in natural abundances. Isotope 34 was selected by a Wien velocity filter. Laser excitation was provided by a CW ring laser operating with the Rhodamine 590 dye. The laser wave-number was measured by an *Angström* WS-U lambdameter, with an accuracy better than 10^{-3} cm^{-1}. Subtracting the photoelectron energy found by analysing the electron interferogram from the photon energy, one can determine the electron affinity ${}^eA$. The result for ${}^eA({}^{34}S)$ is 16 752.978(10) cm^{-1}, to be compared to the previously measured[2] ${}^eA({}^{32}\mathrm{S})$=16 752.976(4) cm^{-1}. Technical correlations between the two measurements lets the isotope shift $\Delta_{exp} = {}^eA({}^{34}S) - {}^eA({}^{32}S)$ be a little more accurate than the more imprecise electron affinity. Numerically $\Delta_{exp} = +0.002(8)$ cm^{-1}, in wich the (2σ) error bars leave room for a normal or anomalous result.

Ab initio calculations of the isotope shift on the electron affinity from the infinite-mass systems S^-/S were carried out, adopting the multiconfiguration Hartree-Fock (MCHF) approach using the ATSP2K package[3]. Our model includes in a systematic way valence correlation, limiting the core to the n=2 shell. The one-electron orbitals are optimized using single- and double- multi-reference expansions. Configuration-iteraction (CI) calculations including up to $6{\cdot}10^5$ configuration state functions were performed in order to complete the convergence patterns of the S^- energy, resulting in a unextrapolated non-relativistic electron affinity of ${}^eA({}^\infty S) = 16\ 987(44)$cm^{-1}. The theoretical isotope shift value $\Delta_{theor} = {}^eA({}^{34}S) - {}^eA({}^{32}S) = -0.0022(2)$cm^{-1} is found to be rather small but definitely negative. The analysis of the various contributions reveals a very large specific mass shift that counterbalances the normal mass shift, while the positive field shift is smaller than the total mass contribution by one order of magnitude.

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On the Importance of an Electric Octupole Contribution to the Radiative Decay of Two Metastable States in Ar^+

P. Quinet[1,2], E. Biémont[1,2], V. Fivet[1], P. Palmeri[1], J. Gurell[3], P. Lundin[3], S. Mannervik[3], L.-O. Norlin[4], P. Royen[3]

[1]*Astrophysique et Spectroscopie, Université de Mons-Hainaut, B-7000 Mons, Belgium*
[2]*IPNAS, Université de Liège, B-4000 Liège, Belgium*
[3]*Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden*
[4]*Department of Physics, Royal Institute of Technology, SE-10691 Stockholm, Sweden*

Most singly charged ions have metastable states that can live very long (lifetimes of the order of seconds or even more). Such levels usually decay to the ground state by magnetic dipole (M1) or electric quadrupole (E2) transitions (denoted 'forbidden transitions'). These second order transitions are generally 10^5–10^8 times weaker than allowed electric dipole (E1) transitions. Higher order transitions, i.e. magnetic quadrupole (M2) or electric octupole (E3) contributions to the decay channels, are generally several orders of magnitude weaker and in most cases negligible.

In the present study, we were interested in the decay properties of the $3s^2 3p^4 (^1D) 3d\ ^2G_{7/2,9/2}$ levels in Ar^+. These metastable states can decay to lower energy levels of the same configuration and of the $3s^2 3p^4 4s$ configuration via M1 and E2 transitions. More interestingly, they can also be connected to the ground term $3s^2 3p^5\ ^2P^\circ$ through higher order transitions, primarily by E3 transitions. These transitions are expected to appear in the UV region (around 65 nm) and the transition probabilities are likely to be enhanced by a strong wavelength effect like the ones observed in Kr II[1] and Xe II[2]. Contrary to these last two cases however, the M2 decay channel is forbidden by the LS selection rules while the E3 transitions are allowed. The importance of a weak E3 transition has previously been reported for Yb II[3].

Using the CRYRING ion storage ring of Stockholm[4], a laser probing investigation has yielded the lifetimes of the $3s^2 3p^4 (^1D) 3d\ ^2G_{7/2,9/2}$ metastable doublet of Ar^+. The results are 3.0 ± 0.4 and 2.1 ± 0.1 s, respectively. Comparisons with theoretical values calculated with two independent approaches, i.e. the pseudo-relativistic Hartree-Fock method and the multiconfiguration Breit-Pauli approach, have allowed us to establish the unexpected and extraordinary strong contribution of the E3 transition to the ground state, in addition to the M1 decay channels to the 3d $^{2,4}F$ states and the E2 contributions to the 4s ^2P, ^2D states. It should be emphasized that this E3 transition is the fastest one (of the order of a tenth of a s^{-1}) ever observed in an experiment. This new result has just been published in PRL[5].

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Atomic Data for Heavy Atoms and Ions (72<Z<86) : A Progress Report

P. Quinet[1,2], P. Palmeri[1], V. Fivet[1], E. Biémont[1,2]

[1]*Astrophysique et Spectroscopie, Université de Mons-Hainaut, B-7000 Mons, Belgium*
[2]*IPNAS, Université de Liège, B-4000, Liège, Belgium*

Our knowledge of the atomic and ionic spectra of the sixth row elements of the periodic table, from Z=72 to Z=86, is still very poor due to the fragmentory laboratory analyses on the one hand and to the complexity of the electronic configurations of the type $4f^{14}5d^{N}nln'l'$ (N=2–10, nl,$n'l'$=6s, 6p, 6d, ...) on the other hand.

The aim of the present work is to provide new radiative data (wavelengths, energy levels, oscillator strengths, radiative lifetimes) as accurate as possible for neutral and lowly ionized platinum group elements. Calculations of atomic structures and spectra in such species are frequently the only way to obtain a large amount of atomic data required by the astrophysicists, particularly for the interpretation of the spectra of chemically peculiar stars and for the study of stellar abundances and nucleosynthesis. Spectroscopic data for some of these elements are also strongly needed for research oriented toward controlled thermonuclear fusion. In particular, radiative properties of tungsten ions are important in connection with the use of this element in fusion reactors.

Such atomic structure calculations, extremely complex, need to be tested by comparisons with experiment in order to deduce some informations about their predictive power. For that reason, we have systematically compared the results obtained with our theoretical models, i.e. the Hartree-Fock approach including configuration interactions, relativistic effects and core-polarization corrections[1,2] with new lifetime measurements carried out using the time-resolved laser-induced fluorescence technique developed at the Lund Laser Centre by Prof. Svanberg and his group.

By combining experimental radiative lifetimes and theoretical branching fractions, we have been able to determine many new oscillator strengths and transition probabilities. The results obtained so far concern the following ions : Ta I (Z=73), W II, W III (Z=74), Re I, Re II (Z=75), Os I, Os II (Z=76), Ir I, Ir II (Z=77), Pt II (Z=78), Au I, Au II, Au III (Z=79), Tl I (Z=81) , Pb II (Z=82) and Bi II (Z=83). These results will be stored in the database DESIRE (**D**atabas**E** on **SI**xth **R**ow **E**lements) on a website of the University of Mons-Hainaut[3,4].

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Theoretical Analysis of Precision Calculation of Helium-like Excited Energy Levels

Xiang Gao[1], Shao-Hao Chen[2], Bo Qing[2], Jia-Ming Li[1,2]

[1]*Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Key Laboratory of Atomic and Molecular Nanosciences of Education Ministry, Department of Physics, Tsinghua University, Beijing 100084, China*

An atomic system with two electrons is a simple nontrivial many-body system. Many theoretical[1,2,3]. and experimental[4,5] works have been done for excited energy levels of the system. For the low Z ions, both theoretical and experimental studies have achieved a very high precision. However, for the high Z ions, the experimental measurements[5] have very large uncertainties while the theoretical calculations may have not considered adequate electron correlations[2,3], relativistic[1] and QED effects[1−3].

In this letter, we analyze our multi-configuration Dirac-Fock(MCDF) calculations of $2^3P_{0,1,2}$ and 2^1P_1 states along Helium isoelectronic sequence[3] quantitatively by an effective Hamiltonian(with approximate physical parameters) which should be valid in all coupling schemes. The physical parameters have their own physical meanings. Our analysis results show that, for lower Z ions, the correlations are the most important effects for the calculation precision and can be precisely corrected based on our MCDF calculations. The competition between Breit and spin-orbit interactions causes interesting variations of $2^3P_{0,1,2}$ fine structure orderings[3]. However, for high Z ions, Breit interactions which represent the relativistic retardation effect of electromagnetic interactions and high order QED corrections are the most important effects for the calculation precision. Such analysis results would be useful for further theoretical precision calculations as well as experimental studies for high Z Helium-like ions, such as the storage ring experiments.

Our analysis is based on the framework of full relativistic QED theory in the Coulomb gauge. For the Dirac-Coulomb and Breit interactions of these states, we use 9 parameters to construct the effective Hamiltonian, as shown in eq.1. Here, a scales as Z^2 and is the statistical average of the 4 excitation energies; b scaling as Z represents the exchange correlations; δ_{so} scales as Z^4 and is for the spin-orbit splittings between $p_{1/2}$ and $p_{3/2}$; d scales as Z and is for relativistic corrections[6] of $p_{1/2}$ and $p_{3/2}$ and $q, \overline{q}, q^*, \overline{q}^*, q'$ scaling as Z^3 are for Breit interactions. Since the high order QED corrections(Self Energy, Vacuum Polarization, etc.) are mainly for single electron, we use one QED parameter for each energy level. The high order QEDs in this work are taken from Drakes results[1] the same way as Johnson did[2]. The high order QED corrections mainly scale as Z^4.

When Z is low, our correlation corrected excitation energies agree with NIST's[7] within 1cm^{-1}; when Z is very high, eg, U^{90+}, the correlation effect is nearly a hundredth of Breit interactions and high order QED effects. Therefore for high Z ions, the Breit and high order QED effects are the most important. Breit interactions can be treated well in our MCDF calculations but further efforts should be made in the high order QED calculations.

$$H_{J=1} = \begin{bmatrix} a-5b/12+\delta_{so}/2-d+q^* & \sqrt{2}b/3+q' \\ \sqrt{2}b/3+q' & a-b/12-\delta_{so}+d+\overline{q}^* \end{bmatrix} \quad \text{and} \quad \begin{cases} H_{J=2} = a+b/4+\delta_{so}/2-d+q \\ H_{J=0} = a+b/4-\delta_{so}+d+\overline{q} \end{cases} \tag{1}$$

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High-Resolution Laser Spectroscopy of a Bose Einstein Condensate Using the Ultranarrow Magnetic Quadrupole Transition

A. Yamaguchi[1,2], S. Uetake[3], S. Kato[1], H. Ito[2], Y. Takahashi[1,3]

[1]*Department of Physics, Graduate School of Science, Kyoto University, Kyoto, Japan*
[2]*National Institute of Information and Communications Technology, Tokyo, Japan*
[3]*CREST, Japan Science and Technology Agency, Saitama, Japan*

The study of laser-cooled two-electron atoms is one of the most interesting research fields in atomic physics. In particular, the unique characteristics of the metastable $^3P_2$ state of two-electron atoms have recently attracted attention both for their applications and study of their intrinsic characteristics.

We report the successful observation of the ultranarrow magnetic quadrupole $^1S_0 \leftrightarrow ^3P_2$ transition in Ytterbium (Yb) (Fig. 1). We first developed a novel 507-nm laser source. By tightly locking the laser frequency to a high-finesse external optical cavity, we stabilized the laser frequency and reduced the linewidth to less than 1 kHz [1]. Using this laser source, we observed the $^1S_0 \leftrightarrow ^3P_2$ transition in Yb bosonic (^{174}Yb) and fermionic (^{171}Yb, ^{173}Yb) isotopes. High-resolution spectroscopy of ultracold atoms and a BEC was performed using this ultranarrow transition. The transition from the Doppler-broadened spectra of thermal atoms to the asymmetric spectra reflecting the inhomogeneous density distribution of BEC in a harmonic trap has been successfully observed (Fig. 1).

We acknowledge Y. Li and M. Hosokawa for their experimental assistances.

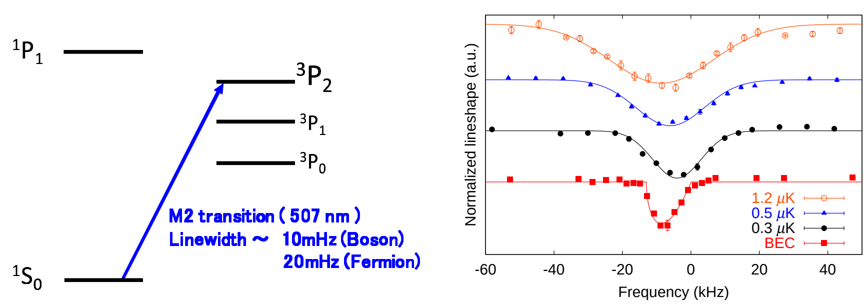

Figure 1: *(Left) Relevant energy levels for Ytterbium. (Right) Observed spectra of the* $^1S_0 - ^3P_2$ $(m = 0)$ *transition in ultracold* ^{174}*Yb atoms and a BEC. A sudden change of the spectrum below the BEC transition is due to the large mean field energy of a BEC.*

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High efficiency frequency upconversion in rubidium vapor

A. Vernier[1], S. Clark[2], S. Franke-Arnold[1], E. Riis[2], A. S. Arnold[2]

[1]*SUPA, Dept. of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK*
[2]*SUPA, Dept. of Physics, University of Strathclyde, Glasgow G4 0NG, UK*

A two-photon near resonant excitation of the Rubidium $5D_{5/2}$ level with 780nm and 776nm pump beams (Fig. 1) leads to the generation of a coherent beam of 420 nm blue light via four-wave mixing due to the strong dipole moment of the 5 μm channel. We have recently obtained more than 1 mW of coherent blue light, exceeding powers in previous experiments[1,2] by a factor of 20 for comparable input powers. We investigate the optimum conditions for the generation of the blue light, and observe that blue power linearly increases with 776 nm power.

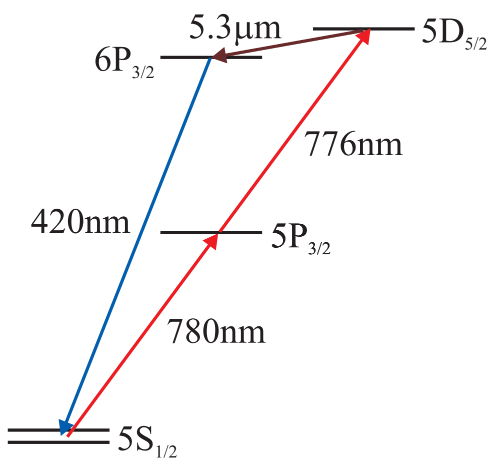

Figure 1: *Rubidium level scheme relevant for blue-light generation.*

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Two photon spectroscopy in atomic hydrogen at 205 nm using a picosecond laser

E. Peters[1], S. Reinhardt[1], S. Diddams[2], Th. Udem[1], T. W. Hänsch[1]

[1]*Max-Planck-Institut für Quantenoptik, Garching, Germany*
[2]*National Institute of Standards and Technology, Boulder, USA*

Atomic hydrogen is the simplest atomic system containing one proton and one electron. The dipole forbidden 1s-2s transition in Hydrogen with a natural linewidth of 1.3 Hz in combination with Doppler-free two photon spectroscopy acts since decades as benchmark for Quantum electrodynamic calculations. For example the Lamb shift measurements of the 1s state started with a relative uncertainty of 9×10^{-2} in 1975 [1] and reached a level of 2.7×10^{-6} in the latest experiments [2].

To improve the accuracy of the 1s Lamb shift and also of the Rydberg constant a measurement of the 1s-3s transition frequency is prepared. For the two photon spectroscopy a wavelength of 205 nm is neccessary, which is produced by two successive second harmonic generations. Using mode locked lasers and resonant second harmonic generation makes the conversion more efficient. As proposed in 1977 [3] a mode locked laser with narrow pulses and its regular mode spectrum can also be a good tool for first order Doppler-free two photon spectroscopy. The frequency modes of the laser adds up in such a way that the linewidth of the resonance is determined by the width of a single mode and not by the pulse duration and the resonance intensity corresponds to the average laser power.

In the presented experiment a commercial picosecond Ti:Sa laser operating at 820 nm is resonantly frequency doubled to 410 nm and in second enhancement cavity the 205 nm is produced. Starting with 1.6 W at 820 nm an output power of 40 mW at 205 nm is achievable [4]. The UV light is further enhanced in linear cavity, designed in such a way that two counterpropagating pulses overlap in the middle of the cavity, where the hydrogen beam crosses the laser beam. The atomic hydrogen beam is produced by a rf-discharge and cooled down to liquid helium temperature to reduce transit time broadening. The excited atoms can decay over the 3s-2p transition at 656 nm that is detected by a photomultiplier.

In the presentation an overview of the setup and the current status is given.

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Laser spectroscopy in wall-coated alkali vapour cells

E. Breschi, G. Mileti

Laboratoire Temps-Frèquence, Université de Neuchâtel, Switzerland

In the fifties pioneering works [1] demonstrated that coating the walls of a glass cell with chemically inert substances reduce the relaxation of the atomic polarization improving the resolution in high precision spectroscopy and metrology. Recently the interest in wall-coated cells is growing again because coated cells represent a good candidate to realize high-performance or micro-quantum sensors[2].

In this communication we report on our preliminary results in laser spectroscopy in paraffin wall-coated Rb vapour cells. In particular we discuss some quality test of the cell based on absorption spectroscopy and our experiments on hyperfine Coherent Population Trapping[3] spectroscopy.

During the experiments, the cell is placed inside both an active and passive magnetic shields (shielding factor $< 10^{-3}$) and a solenoid is used to apply a longitudinal magnetic field on the atomic sample. In the absorption spectroscopy experiments we use single-frequency diode laser and for the CPT experiments the diode laser is modulated through an Electro-Optical Modulator for obtaining the two coherent frequencies necessary to pump the atoms into a dark state.

We are investigating on the possibility to exploit the dependence of the absorption spectrum on the excitation time for first evaluation of the coating quality. The simplicity of this approach from both theoretical and experimental point of view makes it interesting. On the other hand absorption spectroscopy is a relatively low sensitivity technique limiting the information we can get from it. In view of future application in CPT-based atomic clocks, we address our attention to the study of hyperfine ground state coherence relaxation, that has been not systematically studied much so far. Here we discuss the CPT signal linewidth and amplitude depending on some relevant experimental parameters, as the intensity and the linewidth of the laser, and the cell volume. The results are compared with data on Zeeman relaxation obtained in DROM configuration [4].

We thank A. Weis and N. Castagna for the joint DROM measurements and our colleagues of LTF for the useful discussion. This work is supported by the Association Suisse pour la Recherche Horlogère (ASRH), by Swiss National Science Foundation (project 200020-105624) and by the INTAS-CNES (project 06-1000024-9321).

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A high-power, Fourier-transform limited light source for precision spectroscopy in the XUV

K. G. H. Baldwin[1], Mitsuhiko Kono[1], Richard T. White[2], Yabai He[2], Brian J. Orr[2], E. E. Eyler[3]

[1] *Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia*
[2] *MQ Photonics Research Centre, Macquarie University, Sydney, NSW 2109, Australia*
[3] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*

High-resolution laser spectroscopy in the XUV requires pulsed, tunable light sources with high peak powers and narrow optical bandwidths for nonlinear-optical upconversion to generate the required wavelengths. For instance, the $2\,^1S \leftarrow 1\,^1S$ two-photon absorption transition of helium (He) has been measured with narrowband 120-nm radiation generated by pulsed dye amplification of a cw tunable Ti:sapphire laser, followed by nonlinear-optical upconversion.[1]

However, the precision of these VUV spectroscopic studies was limited by degradation of near-infrared optical bandwidth arising from the pulsed dye amplification processes.[1] This arose from shot-to-shot fluctuations in the frequency of the laser pulse (e.g., due to thermal lensing and dye flow inhomogeneities), as well as frequency chirping attributable to the changes in the population inversion of the dye during the pulse.

To circumvent such bandwidth limitations, we employ a high-performance injection-seeded optical parametric oscillator (OPO) based on periodically poled $KTiOPO_4$ (PPKTP) and generating narrowband tunable light pulses at $\sim$840 nm with $\leq$5 μJ energy.[2,3] Population inversion cannot contribute to frequency chirping in this nonlinear-optical approach, which yields well-characterized shot-to-shot frequency stability. Our next step is to amplify the OPO output prior to nonlinear-optical upconversion from $\sim$840 nm to $\sim$210 nm and, ultimately, to $\sim$120 nm.

With the Ti:sapphire-amplified SLM pulsed OPO output at $\sim$840 nm fully characterized, we aim to upconvert it to $\sim$210 nm by successive second-harmonic-generation stages and to test the outcome by recording sub-Doppler two-photon laser-induced fluorescence spectra of krypton (Kr) excited to its $5p[1/2]_0$ state (at $\sim$212.6 nm) and/or of nitrogen (N_2) excited to its $E\,^3\Sigma_g^+$ state (at $\sim$209 nm). Spectroscopic performance tests are considered crucial, as in our previous work on sub-Doppler two-photon spectra of cesium (Cs) at $\sim$822 nm.[3]

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Large scale CIV3 calculations of fine-structure energy levels and lifetimes in Co XV

G. P. Gupta[1], A. Z. Msezane[2]

[1]*Department of Physics, S. D. (Postgraduate) College, Muzaffarnagar - 251 001, (Affiliated to Chowdhary Charan Singh University, Meerut - 250 004), INDIA*
[2]*Department of Physics and Center for Theoretical Studies of Physical Systems, Clark Atlanta University, Atlanta, Georgia 30314, USA*

We have performed large scale CIV3 calculations of excitation energies from ground states for 98 fine-structure levels as well as of oscillator strengths and radiative decay rates for all electric-dipole-allowed and intercombination transitions among the fine-structure levels of the terms belonging to the $(1s^22s^22p^6)3s^23p$, $3s3p^2$, $3s^23d$, $3p^3$, $3s3p3d$, $3p^23d$, $3s3d^2$, $3p3d^2$, $3s^24s$, $3s^24p$, $3s^24d$, $3s^24f$, and $3s3p4s$ configurations of Al-like Cobalt, using very extensive configuration-interaction (CI) wave functions[1]. The important relativistic effects in intermediate coupling are incorporated by means of the Breit-Pauli Hamiltonian which consists of the non-relativistic term plus the one-body mass correction, Darwin term, and spin-orbit, spin-other-orbit, and spin-spin operators[2]. The errors, which often occur with sophisticated *ab initio* atomic structure calculations, are reduced to a manageable magnitude by adjusting the diagonal elements of the Hamiltonian matrices. In this calculation we have investigated the effects of electron correlations on our calculated data, particularly on the intercombination transitions, by including orbitals with up to n=5 quantum number. We considered up to three electron excitations from the valence electrons of the basic configurations and included a large number of configurations (1164) to ensure convergence.

Our calculated excitation energies, including their ordering, are in excellent agreement with the experimental results[3] and the experimentally compiled energy values of the National Institute for standards and Technology (NIST) wherever available. The mixing among several fine-structure levels is found to be very strong, with most of the strongly mixed levels belonging to the $(1s^22s^22p^6)3p^23d$ and $3s3d^2$ configurations. In our CIV3 calculation we identify the levels by their dominant eigenvector[4]. The enormous mixing among several fine-structure levels makes it very difficult to identify them uniquely. Perhaps, this may be the reason that no experimental results are available for these levels. Our very extensive calculations may assist the experimentalists in identifying these fine-structure levels. From our transition probabilities, we have also calculated radiative lifetimes of the fine-structure levels in Co XV. Our calculated lifetime for the level $3s3p^2(^4P_{0.5})$ is in excellent agreement with the experimental value compared to other sophisticated theoretical result. We predict new data for several levels where no other theoretical and/or experimental results are available.

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Fine-structure energy levels and radiative rates for transitions in Mg-like Copper

Vikas Tayal, G. P. Gupta

Department of Physics, S. D. (Postgraduate) College, Muzaffarnagar - 251 001, (Affiliated to Chowdhary Charan Singh University, Meerut - 250 004), INDIA

Emission lines of Mg-like ions are observed in a variety of solar and astrophysical plasmas, and are detected from the UV to the X-ray band. Their emission lines are also widely detected in the spectra of laboratory plasmas, including tokamaks, and are of particular interest in controlled thermonuclear fusion, because they help to estimate the energy loss from the impurities of the reactor walls. Atomic data for parameters such as energy levels, oscillator strengths, radiative decay rates, and collision strengths are required to interpret the plasma observations.

We have performed large scale CIV3 calculation of energy levels and radiative rates for electric dipole transitions among the lowest 141 levels of the $(1s^2 2s^2 2p^6)3l^2$, $3l3l'$ and $3l4l$ configurations of Cu XVIII. These states are represented by very extensive configuration-interaction (CI) wave-functions obtained using the CIV3 computer code of Hibbert[1]. The important relativistic effects are included through the Breit-Pauli approximation[2]. In order to keep the calculated energy splittings close to the experimental values, we have made small adjustments to the diagonal elements of the Hamiltonian matrices.

Our adjusted excitation energies, including their ordering, are in excellent agreement (better than 1%) with the available experimental results[3]. Since mixing among several fine-structure levels is found to be very strong, it becomes difficult to identify these uniquely. In our CIV3 calculations we identified these levels by their dominant eigenvector[4]. From our transition probabilities, we have also calculated radiative lifetimes of some fine-structure levels. Our calculated oscillator strengths, radiative decay rates and the lifetimes are found to be in good agreement with the experimental and other theoretical results (wherever available). We predict new data for several levels where no other theoretical and/or experimental results are available.

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A new method for determining minute long lifetimes of metastable levels

J. Gurell[1], P. Lundin[1], S. Mannervik[1], L.-O. Norlin[2], P. Royen[1]

[1]*Department of Physics, Stockholm University, AlbaNova University Center, SE-10691 Stockholm, Sweden*
[2]*Department of Physics, Royal Institute of Technology, AlbaNova University Center, SE-10691 Stockholm, Sweden*

Radiative lifetime measurements of metastable states have been performed for many years utilizing stored ions. When measuring lifetimes of metastable states in a storage ring the signal may be greatly enhanced, compared to that from passive observation, by actively inducing transitions with one or more lasers. The basic principle of our laser probing technique has been to probe the population of the metastable state as a function of delay time after ion injection which gives us a population decay curve, see *e.g.* Ref. [1]. The introduction of lasers also increases the maximum possible measurable lifetime significantly. Currently the longest radiative lifetime measured at the storage ring CRYRING in Stockholm, Sweden, and to the best of our knowledge in storage rings in general, is 89 s in BaII, see Ref. [2]. For lifetimes longer than this collisional excitation of stored ground state ions becomes a problem since after a few seconds of storage the vast majority of the population of the metastable state under study will be originating from ions that were in the ground state when injected into the storage ring. During the analysis, this contribution is subtracted from the total fluorescence which gives a low S/N ratio, large uncertainties and eventually limits the maximum possible lifetime measurable.

A new method has therefore been proposed and its advantages concerning more accurate lifetime determinations of extremely long lived metastable states demonstrated, see Ref. [3]. Instead of monitoring the decay of the population of the metastable state relative to ion injection the contribution from collisional excitation is monitored directly. In contrast to the metastable state population itself, the collisional excitation grows stronger with increased storage time which results in a much higher S/N ratio at longer storage times and higher residual gas pressures and as a consequence the maximum possible radiative lifetime measurable increases. This technique has so far only been applied in two studies with lifetimes ranging from 16 to 32 s, the 5d $^2D_{5/2}$ state in BaII, see Ref. [3], and the b $^4P_{5/2}$ state in TiII, submitted to J Phys B. This new technique has not yet been pushed to its limit but lifetimes of a few minutes will most probably be possible to measure.

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Theoretical and Experimental Study of Polarization Spectroscopy of Rubidium Atoms

Seo Ro Shin, Geol Moon, Heung-Ryoul Noh

Department of Physics and Institute of Opto-Electronic Science and Technology, Chonnam National University, Gwangju 500-757, Korea

We present an experimental and theoretical (numerical and analytic) study on polarization spectroscopy (PS) of rubidium. The laser-induced birefringence was observed by using linearly polarized probe beam and circularly polarized pump beam. We performed a theoretical calculation of PS spectral based on the rate equation model. All the populations of the magnetic sub-levels were calculated from the rate equations, and used in the calculation of the polarization spectra. Using this model, we could generate theoretical line shapes to make predictions about the general form of the polarization spectra for the D_2 transition of Rb atoms. By comparing theoretical and experimental spectra, we found high agreement in our calculations and experimental data [1].

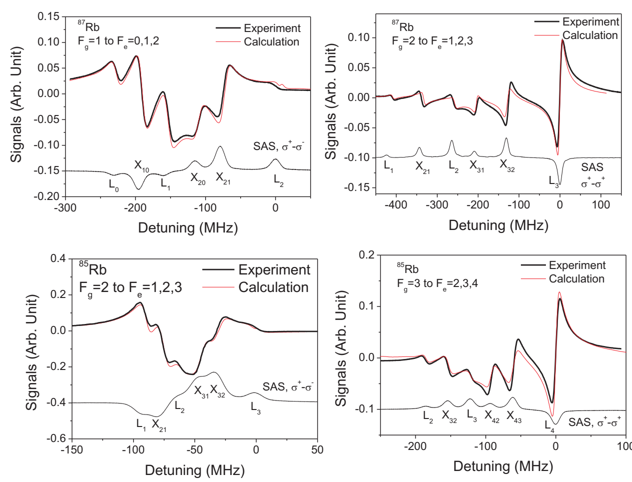

Figure 1: *The experimental and calculated PS spectra for the ^{87}Rb atoms and ^{85}Rb atoms.*

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New data, spin-orbit functions, and potential energy curves for the $A\ ^1\Sigma_u^+$ and $b\ ^3\Pi_{0u}$ states of Cs_2 and Rb_2

H. Salami[1], T. Bergeman[1], A. J. Ross[2], P. Crozet[2], B. Beser[3], J. Bai[3], A. M. Lyyra[3], S. Kotochigova[3], D. Li[4], F. Xie[4], L. Li[4], O. Dulieu[5]

[1]*Department of Physics and Astronomy, SUNY, Stony Brook, NY 11794, USA*
[2]*Universté Lyon 1, CNRS, LASIM UMR 5579, 69622 Villeurbanne, France*
[3]*Department of Physics, Temple University, Philadelphia, PA 19122, USA*
[4]*Department of Physics, Tsinghua University, Beijing 100084, China*
[5]*Laboratoire Aimé Cotton, Université Paris-Sud, 91405 Orsay Cedex, France*

The lowest alkali dimer excited states, $A\ ^1\Sigma_u^+$ and $b\ ^3\Pi_{0u}$, are of particular interest as pathways to the higher states and in the creation of ultracold molecules. The study of these states for the heavy molecules as Cs_2 and Rb_2 is relatively complicated due to the large spin-orbit interactions which mix their potentials. In this study, new data added to the already existing data have been modeled using the Discrete Variable Representation (DVR), so as to fit potential energy and spin-orbit functions.
With the help of high resolution Fourier spectra measured recently at Lyon, we have produced and improved the fit of all available data for the Rb_2 $A\ ^1\Sigma_u^+$ and $b\ ^3\Pi_{0u+}$ states. Vibrational assignments in the A state are unambiguously established and in the b state are strongly probable; we have shifted T_e of the b state by $\pm n\omega_e$ until achieving the best fit. Currently, the rms residual of our fit is 0.07 cm^{-1} while the experimental uncertainty was estimated to be 0.005 cm^{-1}. The potentials are represented by the "Hannover" form.
New low resolution data on Cs_2 $b\ ^3\Pi_{0u\pm}$ states have been obtained in Tsinghua University. Adding these data to data previously obtained from Lab. Aimé Cotton on mixed $A \sim\ b$ states[1,2] has permitted us to characterize the bottom of the potential wells of both the A and the b states. Application of a Morse-Long Range potential[3] has improved the fit in comparison to the Hannover form usually used with DVR method. Currently the rms residual of our fit to the new low resolution data is 1.65 cm^{-1} ($\sim$ experimental uncertainty) and 0.08 cm^{-1} to the older Fourier transform spectroscopy data which has experimental uncertainties of 0.003 cm^{-1}. To reach the levels observed by photoassociation of Feshbach resonances[4], we were forced to extrapolate our potential through a gap of $\sim$800 cm^{-1}, which resulted in a degradation of the rms residual to 0.2 cm^{-1}. Undoubtedly, additional data would be useful, both in regions where no levels have yet been observed, and where few levels with dominant triplet character have been identified.

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Laser Spectroscopy of Exotic Helium Isotopes

I. A. Sulai[1,2], P. Mueller[1], K. Bailey[1], M. Bishof[1,2], R. J. Holt[1], R. V. F. Janssens[1], Z.-T. Lu[1,2], T. P. O'Connor[1], R. Santra[1,2], A. C. C. Villari[3], J. A. Alcantara-Nunez[3], R. Alves-Conde[3], M. Dubois[3], C. Eleon[3], G. Gaubert[3], N. Lecesne[3], M. G. Saint-Laurent[3], J.-C. Thomas[3], G. W. F. Drake[4], Q. Wu[4], L.-B. Wang[5]

[1]*Argonne National Laboratory, Argonne, IL 60439, USA*
[2]*Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[3]*GANIL, Caen, Cedex 05 France*
[4]*Department of Physics, University of Windsor, Windsor, Ontario, N9B 3P4, Caen*
[5]*Los Alamos National Laboratory, Los Alamos, NM 87545*

We have succeeded in laser trapping and cooling of the exotic helium isotopes ^{6}He ($t_{1/2}$ = 0.8 sec) and ^{8}He ($t_{1/2}$ = 0.1 sec), and have performed precision laser spectroscopy on individual trapped atoms. Based on the atomic isotope shifts measured along the isotope chain ^{3}He - ^{4}He - ^{6}He - ^{8}He, and on the precise theory of the atomic structure of helium, the nuclear charge radii of ^{6}He and ^{8}He are determined for the first time in a method independent of nuclear models. The results are compared with the values predicted by a number of nuclear structure calculations and test their ability to characterize these neutron rich, loosely bound halo nuclei. The ^{6}He measurement[1] was performed at ATLAS of Argonne, and the ^{8}He measurement[2] at GANIL, France.
We also report measurements made on ^{3}He where we investigated anomalous strengths of transitions from the metastable 2^3S to the 3^3P manifold[3]. We understand this to be a consequence of strong hyperfine mixing because the hyperfine structure is of the same order of magnitude as the fine structure in ^{3}He.

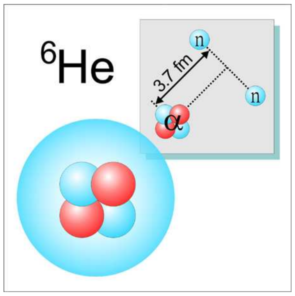

Figure 1: *He-6 nuclei are thought to consist of a He-4 inner core and an outer "halo" part consisting of two more neutrons. The isotope shift measurements reported[1,2] are sensitive to the RMS distance between the alpha particle core and the neutron halo, for both He-6, and He-8.*

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[3]In preparation

Assignment of the RbCs $2^3\Pi_0$, $2^3\Pi_1$, and $3^3\Sigma_1^+$ states and perturbations

Yonghoon Lee[1], Youngjee Yoon[2,5], Soungyul Lee[3], Jin-Tae Kim[4], Bongsoo Kim[2]

[1]*Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea*
[2]*Department of Chemistry, KAIST, Daejeon 305-701, Korea*
[3]*College of Environmental Science and Applied Chemistry (BK21), Kyunghee University, Kyungki-do 449-701, Korea*
[4]*Department of Photonic Engineering, Chosun University, Gwangju 501-759, Korea*
[5]*Current address:Memory Division, Samsung Electronics Co., LTD., Banwol-dong, Hwasung-City, Gyeonggi-do 445-701, Korea*

Alkali metal diatomic molecules have been broadly investigated, both experimentally and theoretically, and have attracted much attention from various fields such as molecular spectroscopy, photodissociation dynamics, and photoassociation spectroscopy. Particularly, recent rapid progress in experiments with ultracold molecules has mainly focused on the heteronuclear alkali dimers since they can be applied to qubit generators for quantum computation.[1] Recently, the low-lying strongly coupled $1^1\Pi$-$2^3\Sigma^+$-$1^3\Pi$ system of heteronuclear alkali dimer RbCs was employed for producing ultracold $X^1\Sigma^+$ RbCs molecules.[2]
We report a newly identified parallel transition of $2^3\Pi_0 \leftarrow X^1\Sigma^+$ and coupled perpendicular transitions of $2^3\Pi$, and $2^3\Pi_1$, $3^3\Sigma_1^+ \leftarrow X^1\Sigma^+$ and observed by mass-resolved resonance enhanced two-photon ionization (RE2PI) in a cold molecular beam of RbCs. Very complex vibronic structures have been observed in our RE2PI spectrum near 640 nm. The $2^3\Pi_0$ state, however, shows a very regular vibronic structure, indicating the absence of significant perturbation. By fitting the observed term values of these parallel bands, we have determined the molecular constants and the Rydberg-Klein-Rees (RKR) potential energy curve of the $2^3\Pi_0$ state.
The origin of the complex vibronic structures has been attributed to strong spin-orbit interactions among the Ω = 1 states. In the lower energy spectral region where the onsets of the $2^3\Pi_1$ and $3^3\Sigma_1^+$ $\leftarrow X^1\Sigma^+$transitions were observed, we have identified the electronic symmetry and the vibrational quantum numbers of the upper vibronic states for the observed perpendicular bands. The diagonal spin-orbit interaction constant of the $2^3\Pi$ state has been estimated from the observed splitting of the electronic term values of the Ω= 0 and 1 components.

The authors are grateful to Dr. Stolyarov for many helpful discussions.

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Light interactions in Rydberg ensembles

K. J. Weatherill, J. D. Pritchard, R. P. Abel, M. G. Bason, A. K. Mohapatra, C. S. Adams

Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK

Atoms in highly excited Rydberg states exhibit strong interactions over distance scales of a few microns. In our work we exploit the enhanced sensitivity of Rydberg states to control the propagation of light through an atomic ensemble. For example, if the atoms are prepared in a dark state corresponding to a superposition of ground and Rydberg states[1] the medium acquires a giant electro-optic effect many orders of magnitude larger than other systems[2]. This giant electro-optic effect can be used to impose sidebands on light propagating through the ensemble as shown in Figure 1a). In ultra-cold ensembles we have observed Rydberg dark states with linewidths of less than 1 MHz (see Figure 1b) and have demonstrated the on-set of interactions effects as the Rydberg density is increased[3]. Our eventual goal is to exploit this giant non-linearity to control pulse propagation at the single photon level.

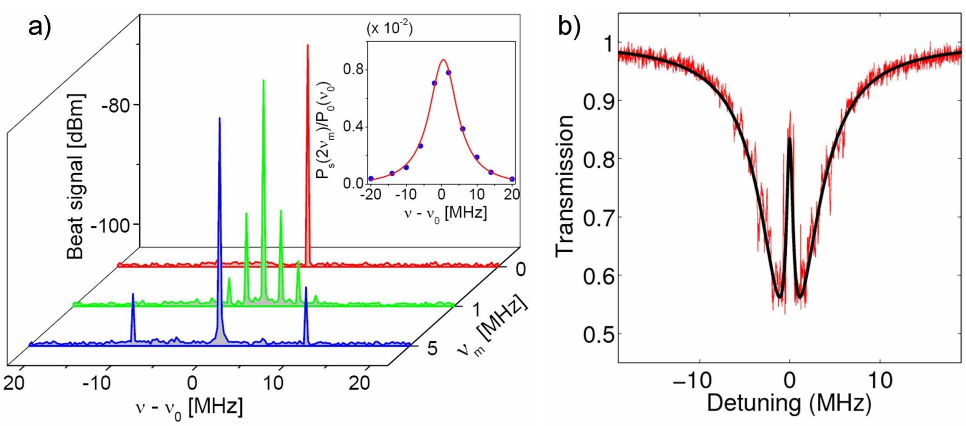

Figure 1: *a) Power spectrum of light transmitted through the Rydberg dark state ensemble showing the generation of sidebands at the* 2^{nd} *harmonic of an applied electric field modulation with amplitude* $3\ \mathrm{V/cm}$ *and frequency* ν_{m}. *Kerr coefficients* $> 10^{-6}\ \mathrm{m/V^2}$ *are measured. Inset: Frequency response of the dark state resonance determined from the sideband intensity. (b) Narrow EIT resonance corresponding to the* $\mathrm{n} = 26\mathrm{d}$ *state in a cold Rb sample. Linewidths of* $\sim\ 600\ \mathrm{kHz}$ *are observed.*

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Theoretical study of the hyperfine structure and isotope shifts in near-infrared transitions of atomic nitrogen

M. Godefroid[1], M. Nemouchi[2], P. Jönsson[3]

[1]*Service de Chimie Quantique et Photophysique, Université Libre de Bruxelles B 1050 Brussels, Belgium*
[2]*Laboratoire d'Electronique Quantique, USTHB, B.P. 32, El-Alia, 16111 Bab-Ezzouar, Alger, Algeria*
[3]*Nature, Environment, Society, Malmö University, Sweden*

Doppler-free spectra of N I transitions on the $2p^2(^3\mathrm{P})3s\ ^4\mathrm{P} \rightarrow 2p^2(^3\mathrm{P})3p\ ^4\mathrm{P}^o$, $^4\mathrm{D}^o$ multiplets have been recorded by Jennerich *et al.* [1] using saturated absorption spectroscopy. From these data, Jennerich *et al.* extracted values for the hyperfine structure coupling constants for the various J levels of these multiplets, for both $^{14}\mathrm{N}$ and $^{15}\mathrm{N}$. Isotope shifts of three transitions in each multiplet have also been measured, revealing a significant J-dependence of the shifts. These authors recommended a theoretical investigation of the undelying cause of this unexpected phenomenon.

In the present work, we report ab initio calculations of hyperfine structure and specific mass shift parameters, together with transition data using the ATSP2K package[2]. Elaborate correlation models within a systematic appoach are used for assessing the reliability of the ab initio parameters. Experimental isotope shift values are critically dependent on the correct interpretation of the hyperfine structures of the $^{14}\mathrm{N}$ and $^{15}\mathrm{N}$ spectra. The specific mass shift parameters calculated for $2p^2(^3\mathrm{P})3p\ ^4\mathrm{P}^o$ and $^4\mathrm{D}^o$ are almost identical and it is hard to propose any mechanism that would cause the observed J-dependency of the isotope shifts. The calculated hyperfine structure constants strongly disagree with experiments, suggesting at this stage that the origin of the problem might be the analysis of the observed hyperfine structures.

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Two-photon spectroscopy of ^{88}Sr

Y. N. Martinez de Escobar[1], P. G. Mickelson[1], S. B. Nagel[1], A. J. Traverso[1], M. Yan[1], T. C. Killian[1], P. Pellegrini[2], R. Côté[2]

[1] *Department of Physics and Astronomy, Rice University, Houston, TX 77074, USA*
[2] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*

We report two-photon photoassociative spectroscopy (PAS) of atomic ^{88}Sr utilizing intermediate states that are weakly bound on the $^1S_0 - {}^3P_1$ potential and determination of the s-wave scattering length a for ^{88}Sr. Two-photon PAS is a powerful tool that finds various applications such as the production of ultracold bound molecules and has been employed to measure the binding energy of weakly bound levels of ground molecular potentials. Furthermore, due to the metastability of the $^3P_1$ state the shape of the excited molecular potential and values of the molecular Franck-Condon factors and atomic dipole matrix elements make spectroscopy near the $^1S_0 - {}^3P_1$ transition differ qualitatively than when using a dipole-allowed transition. Each of these measurements provides accurate determination of a and an understanding of the paths towards quantum degeneracy and the behavior of resulting quantum fluids.

Absolute absorption on the rubidium D lines: comparison between theory and experiment

P. Siddons, C. S. Adams, C. Ge, I. G. Hughes

Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK

Having a theoretical model which predicts the absorption and refractive index of a medium is useful, for example, in predicting the magnitude of pulse propagation effects. We study the Doppler-broadened absorption of a weak monochromatic probe beam in a thermal rubidium vapour cell on the D lines[1]. A detailed model of the susceptibility is developed which takes into account the absolute linestrengths of the allowed electric dipole transitions and the motion of the atoms parallel to the probe beam. All transitions from both hyperfine levels of the ground term of both isotopes are incorporated. The absorption and refractive index as a function of frequency are expressed in terms of the complementary error function. The absolute absorption profiles are compared with experiment, and are found to be in excellent agreement provided a sufficiently weak probe beam with an intensity under one thousandth of the saturation intensity is used. The importance of hyperfine pumping for open transitions is discussed in the context of achieving the weak-probe limit. Theory and experiment show excellent agreement, with an rms error better than 0.2$\%$ for the D_2 line at 16.5°C (see Fig. 1).

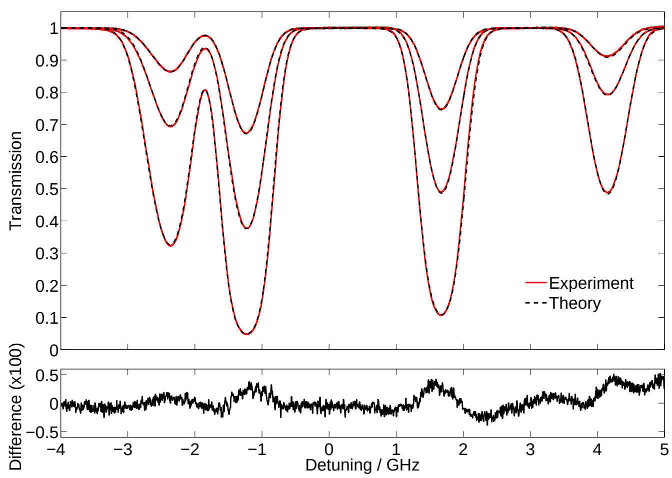

Figure 1: *Transmission plots for the comparison between experiment and theory, at temperatures of $16.5^\circ C$ (top), $25.0^\circ C$ (middle), and $36.6^\circ C$ (bottom). Red and black lines show measured and expected transmission respectively. Below the main figure is a plot of the difference in transmission between theory and experiment for the $16.5^\circ C$ measurement.*

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Optical pumping effect on the magnetic field dependent intensity of hyperfine split D_1, D_2 lines of ^{85}Rb and ^{87}Rb

M. Ummal Momeen, G. Rangarajan, P. C. Deshmukh

Department of Physics, Indian Institute of Technology- Madras, Chennai- 600 036, India.

The intensity of Zeeman components of rubidium (^{87}Rb and ^{85}Rb) hyperfine split D_1 and D_2 lines has been studied up to a field of 5mT. Saturation absorption spectroscopic technique is used to resolve the hyperfine spectrum. Optical pumping effect in the closed transition (F=2 to F'=3 in ^{87}Rb and F=3 to F'=4 in ^{85}Rb D_2 line) is reported. All possible polarization configurations (π, σ_+, σ_-) have been employed for the pump and probe beams. Tremblay's field induced transition probability[1], Nakayama's four level model[2] were already used by us to compute the field dependent intensity variation[3]. These calculations have now been refined taking into account multi- cycle pumping[4]. The experimental and calculated results are compared.

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Saturation spectroscopy of the 372 nm Fe I resonance line with laser diode radiation

S. Krins, P. Saint-Georges, T. Bastin

Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, Belgium

Saturation spectroscopy is a well known technique to get Doppler-free spectral lines of elements at ultra-high resolution. It is also a popular technique to stabilize precisely laser radiation within atomic linewidths. Here we report preliminary results about absorption saturated spectra of the resonance line $3d^6 4s^2\,{}^5D_4 \rightarrow 3d^6 4s4p\,{}^5F_5^o$ of iron atoms at 371.9935 nm using a low power commercial laser diode. The scheme of the experimental setup is shown on Fig. 1. A UV laser diode delivering a 4 mm^2 5 mW laser beam is sent partly to a saturation spectroscopy setup and crosses an iron vapor cell. Iron atoms are produced in a home made Fe-Ar hollow cathode discharge cell[1]. The laser beam is sent backwards to the hollow cathode and is superimposed exactly to the pump beam in combination with a $\lambda/4$ waveplate to extract the 90° polarization rotated probe beam at the exit of the hollow cathode. Good signal to noise ratios in the saturated absorption spectra have been obtained, demonstrating the suitability of commercial UV laser diodes for this purpose and their ability to be easily stabilized at this wavelength for any application requiring such radiation. In this way we extend to small UV laser diode systems the results obtained by Smeets *et al.*[2] with a doubled frequency titanium sapphire laser.

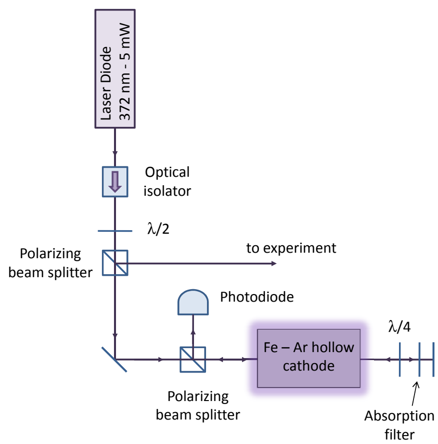

Figure 1: *Experimental arrangement.*

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Potassium ground state scattering parameters and Born-Oppenheimer potentials from molecular spectroscopy

St. Falke[1,2], H. Knöckel[1], J. Friebe[1], M. Riedmann[1], E. Tiemann[1], Ch. Lisdat[3]

[1]*Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*
[2]*Department of Physics, Yale University, New Haven, CT, USA*
[3]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

We present precision measurements with MHz uncertainty of the energy gap between asymptotic and well bound levels in the electronic ground state X $^1\Sigma_g^+$ of the $^{39}K_2$ molecule. The molecules are prepared in a highly collimated particle beam and are interrogated in a Λ-type excitation scheme of optical transitions to long range levels close to the asymptote of the ground state, using the electronically excited state A $^1\Sigma_u^+$ as intermediate one.[1] The transition frequencies are measured either by comparison with I_2 lines or by absolute measurements using a fs-frequency comb. The asymptotic levels were observed for the first time and extend the existing datafield[2] to within 0.2 cm^{-1} of the dissociation energy. The determined level energies were used together with Feshbach resonances from cold collisions of ^{39}K and ^{40}K reported from other authors[3] to fit new ground state potentials. Precise scattering lengths are determined and tests of the validity of the Born-Oppenheimer approximation for the description of cold collisions at this level of precision are performed. This is of particular importance if one aims for describing Feshbach resonance positions of several isotope combinations by a single model.

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Tomography of a cold molecular beam via cavity-enhanced direct frequency comb spectroscopy

M. J. Thorpe, F. Adler, K. C. Cossel, J. Ye

JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440

The emerging field of cold molecules and cold chemistry will require spectroscopic probes capable of investigating large energy scales at high resolution[1]. Cavity-enhanced direct frequency comb spectroscopy combines broad spectral bandwidth, high spectral resolution, precise frequency calibration, and high detection sensitivity, all in one experimental platform[2]. This spectrometer is ideal for studies of the quantum state distributions, density profiles, velocity distributions, and interactions of cold molecular ensembles. To develop and refine this novel spectroscopic technique we have performed tomographic studies of a supersonically cooled beam of acetylene molecules[3]. Absorption measurements are recorded at a variety of positions within the supersonic jet allowing for a direct observation of beam dynamics. A high resolution spectrometer in cavity transmission records 25 nm snapshots of the molecular absorption spectrum while providing resolutions as low as 200 kHz (Fig. 1). The broad bandwidth and high resolution allow for simultaneous observation of internal state distributions and external degrees of freedom as the beam cools (Fig. 2a,d). An inverse Abel transform is applied to the integrated absorption measurements to generate molecular density profiles revealing the internal and external state dependances of the molecular density within the beam[4] (Fig. 2b,c).

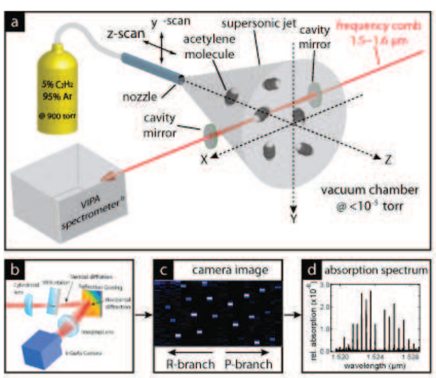

Figure 1. (a) The experimental setup. (b) VIPA spectrometer. (c) Camera image revealing molecular absorption. (d) C_2H_2 absorption spectrum generated by unwrapping camera image.

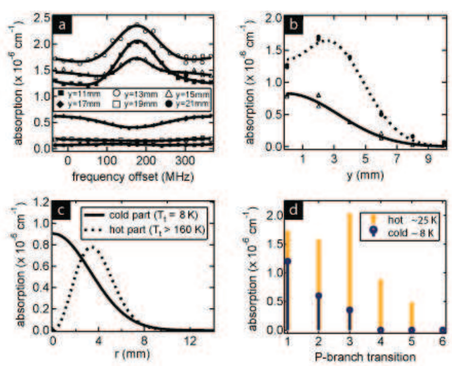

Figure 2. (a) Scan of (ν1+ν3)-R(0)-line over one cavity FSR for different height positions. (b) Hot and cold portions of the beam. (c) Inverse Abel transform, representing radial absorption distributions. (d) P-branch rotational distributions for hot and cold velocity groups.

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Analytic Solutions for the Saturated Absorption Spectra at low intensity

Geol Moon, Seo Ro Shin, Heung-Ryoul Noh

Department of Physics and Institute of Opto-Electronic Science and Technology, Chonnam National University, Gwangju 500-757, Korea

We present analytic solutions for the saturated absorption spectroscopy(SAS) spectra based on a rate equation model. The model can provide accurate SAS spectra under all experimental conditions (for various pump beam intensities and diameters) without the need for phenomenological constants. The rate equations governing the dynamics of the populations in the presence of a pump laser beam were solved analytically. The SAS spectra were then calculated using the analytic solutions of the populations. The calculation was carried out for the D_2 transition line of the ^{87}Rb atom. One of the assumptions of this method is the large energy spacing between the hyperfine levels of the excited state, which means that the optical pumping to other excited state hyperfine levels can be neglected. Therefore, this method can be better applied to ^{87}Rb or Cs rather than ^{85}Rb or Na. The polarization scheme of the pump and probe beams under consideration is $\sigma^+ - \sigma^+, \sigma^+ - \sigma^-, \pi \parallel \pi$ and $\pi \perp \pi$. We compared the analytic solutions with the numerical and experimental results and found good agreement between them[1].

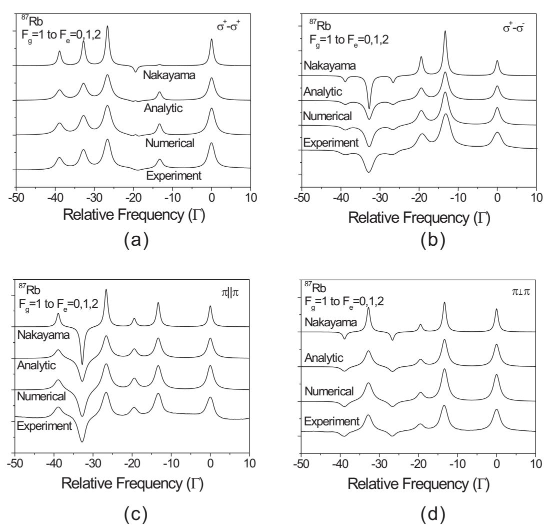

Figure 1: *Experimental, numerical, analytic, and Nakayama's results for the SAS spectra at the transition $F_g = 1 \rightarrow F_e = 0, 1, 2$ when the pump-probe polarization configurations are (a)$\sigma^+ - \sigma^+$, (b)$\sigma^+ - \sigma^-$, (c)$\pi \parallel \pi$, and (d)$\pi \perp \pi$.*

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Cold Atoms Microwave Frequency Standards in Brazil

S. T. Müller[1], R. F. Alves[1], A. Bebeachibuli[1,2], D. Lencione[1], V. S. Bagnato[1], D. V. Magalhães[1]

[1]*Instituto de Física de São Carlos, São Paulo, Brazil*
[2]*Observatório Nacional do Rio de Janeiro, Rio de Janeiro, Brazil*

Our group has been working in the development of primary frequency standards. These include experiments with Cs atoms in an atomic fountain and cold atoms within a microwave cavity. This last concerns the construction of a magneto-optical trap inside a microwave cylindrical cavity, tuned to the $F = 3, m_f = 0 \rightarrow F = 4, m_f = 0$ ground state transition, and we will report the last advances on it. We worked in a model to explain the poor contrast we observed in preliminary tests using cold atoms and a microwave antenna. This model includes the microwave field distribution and the free expansion of the cold atoms cloud. It was applied to both one and two oscillatory fields interrogation methods, showing good agreement with the acquired data. The other experiment concerns the development of an atomic fountain to be used as a frequency standard. We report the last results obtained for this system, related to first stability evaluations and analysis of frequency shifts. We will also show the structure that is under development to provide capabilities of evaluating these standards and a future link with TAI (International Atomic Time).

Investigation of the optical transition in the ^{229}Th nucleus: Solid-state optical frequency standard and fundamental constant variation

Eric R. Hudson, A. C. Vutha, S. K. Lamoreaux, D. DeMille

Department of Physics, Yale University, 217 Prospect Street, New Haven, CT 06511, USA

The technological impact of atomic clocks has been profound. High-precision clocks have also provided a means to probe fundamental issues in physics. Already, atomic clock experiments have provided some of the most stringent tests of General Relativity[1] and produced the tightest constraints on present day variation of many of the fundamental constants[2]. It appears universally recognized that the most promising route to improved clocks uses reference oscillators based on optical transitions; already, two such experiments have reported better stability than the primary Cs standard[2,3].

Despite their successes, traditional clock experiments are often cumbersome. To mitigate environmental influences on the reference oscillator transition, modern clock experimenters routinely employ complicated interrogation schemes such as atomic fountains or optical lattice confinement. An interesting shift in paradigm is to consider an optical clock based on a nuclear transition. Just as in atomic clocks, the high Q oscillator, *i.e.* the nuclear transition, can in principle be addressed by laser spectroscopic techniques, as long as the transition energy is accessible with current laser technology. However, as is well-known from Mössbauer spectroscopy, nuclear transitions are relatively insensitive to their environmental surroundings compared to atomic transitions. Thus, the complicated apparatus of an optical atomic clock may be replaced by a single room-temperature crystal doped with an appropriate nucleus.

We present a proposal for the the construction of a frequency standard based on an optical transition in the ^{229}Th nucleus. Recent data indicates that this transition has the lowest energy of any known nuclear excitation[4], which should make it amenable to study by laser spectroscopy when embedded in a VUV-transparent crystal. Detailed analysis of the crystalline environment leads us to expect that the magnetic dipole-dipole interaction between adjacent nuclei will be the dominant transition broadening mechanism, increasing the transition linewidth from its natural value of $\approx$10 μHz to $\approx$3 Hz. When coupled with the large number of atoms that can be doped into a solid, an improvement in the quantum projection noise limit of as much as 10^6 over current optical clocks may be possible. Furthermore, because of the larger energy scales inherent to nuclear interactions, this transition has $10^3 - 10^5$ times more intrinsic sensitivity to variations in the fundamental constants. The construction of the system appears to be surprisingly easy, as preliminary crystals doped with the (more stable) ^{232}Th isotope have already been produced.

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Trapped Atom Clock on a Chip

F. Reinhard[1], C. Lacroûte[2], T. Schneider[3], J. Reichel[1], P. Rosenbusch[2]

[1] *Laboratoire Kastler-Brossel, 24 rue Lhomond, 75231 Paris CEDEX 05, France*
[2] *SYRTE - Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France*
[3] *present address: Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, 40225 Düsseldorf, Germany*

We are developing a compact atomic clock based on the atom chip technology, intended to be a secondary standard. Its frequency reference is the transition between the two magnetically trapped hyperfine sublevels $|F = 1, m_F = -1\rangle$ and $|F = 2, m_F = 1\rangle$ of the ground state of ^{87}Rb. This transition will be interrogated using a two-photon, microwave and RF, Ramsey excitation scheme [1]. The interrogation of trapped atoms has the advantage of long Ramsey times ($>$ 1s), realisable in a compact setup. We will perform the interrogation on a thermal cloud or a BEC, thereby exploring the application of BEC in metrology. Inspired by the proof–of–principle experiment [2] we have constructed a dedicated setup, which is now nearly operational.
The clock stability of the proof-of-principle experiment was 10^{-11} at 1s, limited by trivial technical imperfections, most notably magnetic field noise. Therefore, our new setup includes two layers of magnetic shielding and the detection of both hyperfine states. Furthermore, we have integrated a microwave transmission line on the chip whose evanescent field will couple the interrogation microwave to the atoms. These wires replace the microwave cavity used in fountain clocks. We expect these improvements to earn us a stability in the 10^{-12} at 1s range. Assuming further improvements on the atom number and the cycle time, a stability in the low 10^{-13} at 1s range seems feasible. A clock with this performance would outperform today's best commercial atomic clocks by one order of magnitude, while being much smaller than the atomic fountain primary standards. This combination of features opens a clear perspective for applications like satellite navigation.
Ultimately, the clock stability will be limited by the finite coherence time, which is governed by dephasing between atoms with different trajectories due to the trap-induced shifts. The major frequency shift is the Zeeman shift induced by the trapping field. Its first-order contribution is common-mode for both clock states. Its second order contribution exhibits a minimum at the magic field of 3.23G, where the transition frequency is shifted by 4.5kHz from its zero-field value [3]. However, it is favorable to operate the clock trap slightly below this magic field, in a region where this second order Zeeman shift cancels the collisional shift [4] . We find that in a shallow trap of $(5, 300, 300)$Hz, whose trap bottom is detuned by -0.05G from the magic field, the frequency spread averaged over a cloud of 10^5 atoms and 0.5μK can be as small as 0.17Hz.

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Spin squeezing on the Cs clock transition by QND measurements in a cold atomic ensemble

U. Hoff, P. Windpassinger, D. Oblak, J. Appel, N. Kjærgaard, E. S. Polzik

QUANTOP - Danish National Research Foundation Center for Quantum Optics, Niels Bohr Institute, Copenhagen University, Denmark

We investigate the concept of spin squeezing on the cesium clock transition in a cold and dipole trapped atomic ensemble. The collective atomic state is described in terms of a pseudo-spin, where the z-component represents the population difference between the clock states. The Cs sample is located in one arm of a Mach-Zehnder interferometer and the atomic level population difference is probed non-destructively by measuring the dispersive phase shift of off-resonant light, caused by the state-dependent index of refraction of the atoms. By applying a near-resonant microwave field on the clock transition we can control the evolution of the collective atomic quantum state and steer the pseudo-spin vector on the Bloch sphere. Combining these techniques we are able to prepare the atomic ensemble in a coherent superposition of the clock states and perform QND measurements of the level population difference. The measurement statistics reveal the atomic projection noise. Furthermore, we observe correlations between consecutive measurements on the same atomic sample, indicating that conditional squeezing of the atomic pseudo-spin has be achieved. In that case, the outcome of one measurement can be used to predict the outcome of a subsequent measurement with a precision better than the standard quantum limit.

Reducing Clock Projection Noise with Measurement-Induced Correlations

M. H. Schleier-Smith, I. D. Leroux, V. Vuletić

MIT-Harvard Center for Ultra-Cold Atoms, Research Laboratory of Electronics and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

For nearly a decade, the best atomic clocks have been limited by atomic shot noise[1], the statistical uncertainty in the result of projecting an ensemble of independent and uncorrelated atoms onto the eigenstates of a measurement. It is possible to go beyond this limit by entangling or correlating the atoms, so that the outcome of a collective measurement is no longer the simple average of independent measurements on each atom[2]. In the Bloch sphere representation, where each (two-level) atom is represented as a spin-$1/2$ and the collective state of an ensemble of N identically-prepared atoms behaves as an angular momentum $S = N/2$, these correlations between atoms correspond to spin squeezing; i.e. to reducing one of the two uncertainty components perpendicular to the mean angular momentum vector below the value of $\sqrt{S/2}$ found in the coherent (uncorrelated) state[3].

Such a squeezed or correlated state can be prepared by projective measurement; for instance by a sensitive measurement of the relative population of the two clock states—corresponding to the z component of the collective spin—of an ensemble of atoms initially prepared in an equal superposition of those two states, i.e. in the xy plane of the Bloch sphere. This requires that the measurement be more precise than the intrinsic $\sqrt{S/2}$ uncertainty of the initial uncorrelated coherent state and that it be non-destructive. The latter requirement means that the magnitude of the effective angular momentum vector, or equivalently the permutation symmetry of the collective atomic state, must not be altered by the measurement. In particular, the measurement must not allow the state of individual atoms to be determined. Practically, this requirement implies the preservation of the clock fringe contrast.

Using a sample of ^{87}Rb atoms confined in an optical resonator (total optical depth ~ 6000) and prepared in a superposition of the two states of the $|F = 1, m = 0\rangle \leftrightarrow |F = 2, m = 0\rangle$ hyperfine clock transition, we have used the atom-induced shift of a cavity resonance to implement such a measurement of relative population. We have reached a sensitivity 7dB below the shot noise limit without a commensurate reduction in fringe contrast, for a net 4dB of squeezing. We have thus created an entangled collective state with reduced fluctuations in one quadrature of the collective spin that may be used to improve the precision of an atomic clock.

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Progress toward Sr Optical Lattice clock at NICT and Vapor Cell Measurement of ^{88}Sr $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_1$ Collision Shifts

N. Shiga*, Y. Li, S. Nagano, H. Ito, H. Ishijima, A. Yamaguchi, M. Koide, R. Kojima, M. Kajita, M. Hosokawa, T. Ido

National Institute of Information and Communications Technology (NICT), Tokyo, Japan
**email: shiga@nict.go.jp*

We are building a Sr optical lattice clock at NICT. Our mission is to obtain and deliver the stable frequency standard in Japan and the Sr atomic clock will provide one of the secondary representations of the second. Our latest progress is that we have trapped the ^{88}Sr atoms in a 461 nm Magneto-Optical Trap (blue MOT).

In order to estimate the order of collision shift in $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_0$ clock transition, we measured the collision shifts in the ^{88}Sr $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_1$ transition (λ=689 nm). We performed saturation absorption spectroscopy of thermal atoms in a vapor cell at 455 $^\circ$C, and the absolute frequency of 689 nm laser was calibrated with a frequency comb which was referenced to International Atomic Time (TAI). This scheme enabled us direct comparison of our cell-based measurement to the accurate frequency obtained with ultracold atoms[1]. We measured the shift due to Sr-Sr binary collisions, as well as collisions with helium, neon and argon buffer gas. The observed shift due to collisions with helium was $\sim$+5 kHz at 10^{-2} Torr. If we assume linear scaling, the shift would be $\delta f/f \sim 10^{-18}$ at 10^{-9} Torr. While our measurement is not directly on $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_0$ clock transition, this measurement may add extra information on the systematic shift of the clock transition at the level of $\delta f/f \sim 10^{-18}$.

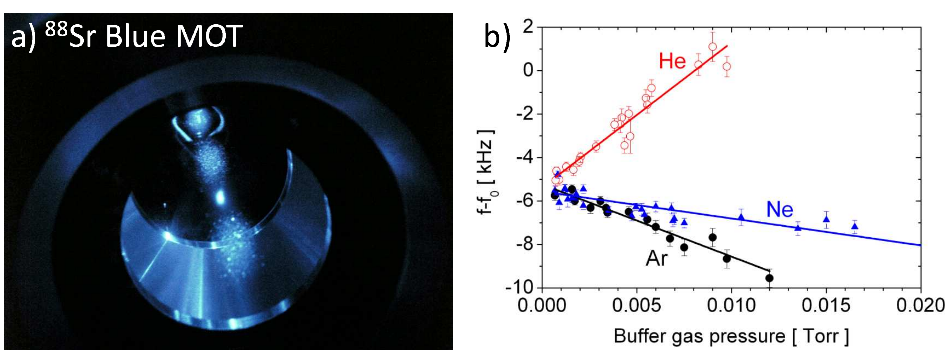

Figure 1: *a) ^{88}Sr trapped in a blue MOT. b) Collision shift dependence on background gas pressure. f_0 is the frequency measured in ref. 1.*

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Optical Lattice Clocks with Single Occupancy Bosons and Spin-Polarized Fermions

M. Takamoto[1,2], T. Akatsuka[1,2], H. Katori[1,2]

[1]*Department of Applied Physics, Graduate School of Engineering,*
The University of Tokyo, Bunkyo-ku, 113-8656 Tokyo, Japan.
[2]*CREST, Japan Science and Technology Agency,*
4-1-8 Honcho Kawaguchi, 332-0012 Saitama, Japan.

To date, optical clocks based on singly trapped ions and ultracold neutral atoms trapped in the Stark-shift-free optical lattices [1] are regarded as promising candidates for future atomic clocks. So far "optical lattice clocks" have been evaluated with uncertainty of 1×10^{-15} on the basis of the Cs atomic clocks [2]. However, the latter performance is not enough to fully evaluate the former stability as well as accuracy. Therefore, frequency comparison between highly-stable and accurate optical lattice clocks is crucial for this evaluation. Furthermore, one of the essential experimental challenges in the development of optical lattice clocks is to find out the better lattice geometries as well as interrogated atom species [3] (including their quantum statistics) that bring out the potential performance of the clock scheme.

We discuss two possible configurations for optical lattice clocks; three-dimensional (3D) lattice loaded with bosons and one-dimensional (1D) lattice loaded with spin-polarized fermions [4]. In the former scheme, a single occupancy lattice suppresses bunching of bosons and collision shifts. While in the latter scheme, collisional frequency shift is suppressed by the quantum statistical property of identical fermions. This Pauli blocking of collisions, therefore, critically depended on the degree of spin polarization of fermionic atoms, which we carefully investigated in the Rabi excitation process of the clock transition.

We will present frequency comparison of these two optical lattice clocks based on fermionic ^{87}Sr and bosonic ^{88}Sr. By operating these clocks sequentially[5], we achieved the stability 5×10^{-16} after $2,000$ s averaging time. Such measurements will offer an important step to ascertain the lattice clocks' uncertainty at the 10^{-16} level and beyond, where no working standard exists.

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Laser-cooled atoms coupled to a magnetic micro-cantilever

A. Geraci, Y.-J. Wang, M. Eardley, J. Moreland, J. Kitching

Time and Frequency Division, NIST, Boulder, CO 80305

Micro-cantilevers have demonstrated remarkable force sensitivity, while dilute atomic gases can exhibit long coherence times and on-chip atomic systems have proven to be useful for quantum control and manipulation. The direct coupling of the spin-degrees of freedom of an atomic vapor to the vibrational motion of a magnetic cantilever tip has recently been demonstrated[1], and prospects for coupling a BEC on an atom-chip to a nano-mechanical resonator have been recently discussed[2]. Possible applications include chip-scale atomic devices, in which localized interactions with magnetic cantilever tips selectively influence or probe atomic spins. As a next step towards the realization of a strongly coupled ultra-cold atom-resonator system, we have constructed an apparatus to study the direct coupling between the spins of an ensemble of laser-cooled Rb atoms and a magnetic tip on a micro-cantilever. The cantilever with magnetic tip is shown in Fig. 1. The atoms will be loaded from a Magneto-Optic-Trap (MOT) into a magnetic quadrupole trap formed by the cantilever tip and external magnetic fields. The cantilever will be driven capacitively at its resonance frequency ($\sim$MHz), resulting in a coherent precession of the trapped atomic spins with a matching Larmor frequency. Such spin precession can be observed by monitoring trap loss through fluorescence or by optical detection of the rotation of the atomic magnetization. Prospects for measuring the back-action of the ensemble of atomic spins on a cantilever beam will also be discussed. Ultimately, if a particular cantilever mode can be cooled to the single-phonon level perhaps in a cryogenic experiment with additional feedback cooling, non-classical states of the atomic degrees of freedom could be transferred to the motional states of the resonators and vice versa, possibly leading to novel tests of quantum mechanics at macroscopic scales.

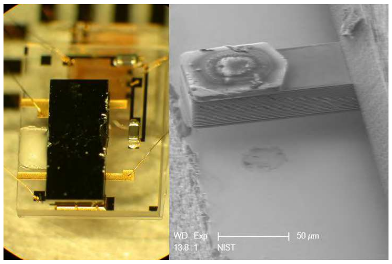

Figure 1: *(left) Optical micrograph of cantilever capacitive drive stack and (right) SEM micrograph of Si cantilever with electroplated CoNiMnP magnet.*

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[2] Philipp Treutlein, David Hunger, Stephan Camerer, Theodor W. Hansch, and Jakob Reichel, Phys. Rev. Lett. **99**, 140403 (2007).

Microwave Power Measurements Using Rabi Oscillations

Alain Michaud, David C. Paulusse, Chantal Prévost

National Research Council Canada, Ottawa, Canada K1A 0R6
(Alain.Michaud@nrc-cnrc.gc.ca)

A quantum-based microwave powermeter has been proposed a while ago, and measurements have shown that it could lead to the development of a laboratory standard. [1] [2] [3]

Rabi flopping oscillation is a very common phenomenon. Although it has been studied and used extensively, it is only since the introduction of laser cooling techniques, that it would become possible to use the hyperfine interaction as a tool for the precision measurement of the RF field amplitude (power).

The system uses a standard Magneto-Optical Trap as the source of cold atoms. The cold atoms are simply dropped, and later cross a rectangular waveguide transmission line, where the RF field amplitude is to be measured. The atoms probe the RF field and are later probed by a laser beam.

A short section of rectangular metal waveguide constitutes the vacuum chamber. The top and bottom holes where the atoms cross the guide are equipped with cutoff tubes to prevent RF leakage, and the vacuum windows inside the guide are frequency tuned (6.8 GHz) to prevent any standing wave. The incident RF power through the chamber measured by classical techniques such as thermistor-mount or calorimeter.

In order to compare both classical and atomic standards, we plot the population inversion vs the field amplitude. By fitting the frequency of these (Rabi) oscillations, we find the calibration factor of the powermeter and we can also study its linearity.

The system was designed for low level measurements ie, the dropping distance is low which results in an interaction time of about 15 ms. The obtained resolution is about 0.1 % after 60 Rabi cycles ($\approx$ 2 mW). For this power level, the accuracy is limited by the uncertainty on the interaction time. We deduce the transit time in the the waveguide by measuring the initial position of the MOT. This technique leads to a high uncertainty at a low drop distance and a better technique found for the determination of the interaction time.

The paper describes the apparatus, and the measurement techniques.

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[2] T.P. Crowley, E.A. Donley and T.P. Heavner, "Quantum-Based Microwave Power Measurements: Proof-of-concept Experiment.", in *Rev. Sci. Instrum.* Vol. 75, no, 8 pp. 2575-2580, 2004. DOI: 10.1063/1.1771501

[3] D.C. Paulusse, N.L. Rowell and A. Michaud, "Accuracy of an Atomic Microwave Power Standard.", *IEEE Trans. Instr. Meas.*, Vol 54. no 2 pp. 692-695. online: http://arxiv.org/physics/0503111

Quantum optics near surfaces

H. Bender, Ph. W. Courteille, C. Zimmermann, S. Slama

Institute for Physics, University of Tübingen, Auf der Morgenstelle 14, Tübingen, Germany

The main focus of our experiments is the behavior of matter waves which are prepared at a very low distance to a surface. There atom-surface interactions like the Casimir-Polder (**CP**) force play a dominant role.
In our case the surface is the facet of a glass prism. The evanescent wave of a laser beam which is reflected at this facet will allow us to add short range dipole potentials acting on the atoms. A laser beam which is blue-detuned to the D2 line of ^{87}Rb will make a repulsive potential decreasing exponentially with the distance from the surface. This steep potential compensates for the attractive CP-force and thus forms a controllable barrier at a distance of a few hundred nanometers from the surface.

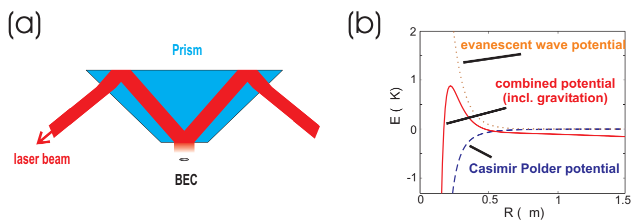

Figure 1: ***(a)*** *Experimental setup: A BEC is placed below the surface of a prism in the evanescent wave of a reflected laser beam* ***(b)*** *Barrier formed by the superposition of CP- and evanescent wave dipole-potential*

Matter-waves propagating towards this barrier may either be reflected or transmitted. The reflectivity of the barrier is determined by its height compared to the kinetic energy of the matter-waves. Measuring the reflectivity as a function of the barrier height will thus allow us to deduce the CP-potential.

A short-time perspective of measurements also includes a nondestructive measurement of the atom number in a Bose Einstein Condensate (**BEC**). A BEC overlapping with the evanescent wave of a far detuned laser beam will shift the phase of the reflected light by an amount of the order of 10^{-4} rad. Monitoring this phase shift as a function of time will provide information about atom number fluctuations in a BEC.

In the long term we plan to tailor nano potentials on the surface by means of surface plasmon polaritons (**SP**). Deposition of metal layers on the prism surface which are structured on the nanometer scale should allow for a local excitation of SPs. The light-induced oscillation of the electrons in these layers strongly enhances the electrical field of the evanescent dipole potential. The implementation of such potentials opens up possible applications in quantum information.

Realization of localized Bohr-like wavepackets

J. J. Mestayer[1], B. Wyker[1], J. C. Lancaster[1], F. B. Dunning[1], C. O. Reinhold[2,3], S. Yoshida[4], J. Burgdörfer[4,3]

[1] *Department of Physics and Astronomy and the Rice Quantum Institute, Rice University, Houston, TX 77005-1892, USA*
[2] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6372, USA*
[3] *Department of Physics, University of Tennessee, Knoxville TN 37996, USA*
[4] *Institute for Theoretical Physics, Vienna University of Technology, Vienna, Austria, EU*

We present a protocol and its experimental realization for the formation of the original Bohr atomic model,[1] an electron revolving around the nucleus on a (near) circular orbit.
Highly-excited Rydberg atoms in circular states are characterized by extremely high values of one component of the angular momentum $\langle L \rangle \sim \pm(n-1)\hbar$, where n is the principal quantum number. Stationary high-l states have become accessible via laser excitation in external fields.[2] The development of ultrafast electromagnetic pulses[3] opens up the possibility of engineering non-stationary circular wavepackets which resemble a localized quasi-classical electron moving in a Kepler orbit.
Here we experimentally and theoretically demonstrate the creation of such wavepackets near $n \sim 300$ which behave much as a classical electron in a nearly circular Kepler orbit. The motion of the wavepackets can be followed for several Kepler periods and provides a direct analog of the original Bohr atom.[4] Such Bohr-like wavepackets could represent an important stepping stone towards realization of phase-locked correlated planetary configurations in multi-electron atoms.

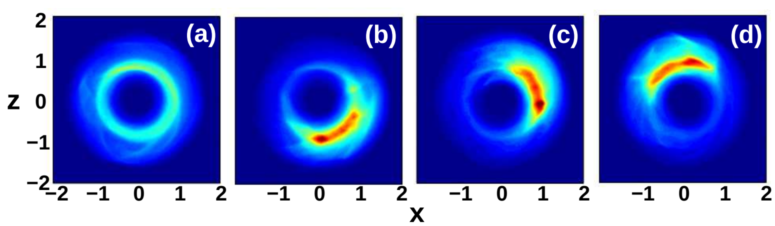

Figure 1: *Circular state (a) and electron wavepacket on Bohr orbit (b-d) in K ($n \sim 300$) after laser excitation and application of a half-cycle pulse.*

[1]N. Bohr, Phil. Mag. 26, 1 (1913)
[2]R.G. Hulet and D. Kleppner, Phys. Rev. A 51, 1430 (1983)
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[4]J.J. Mestayer et al. Phys. Rev. Lett. (2008, in print)

Earth-Field Self Oscillating Magnetometer

J. M. Higbie[1], E. P. Corsini[1], D. Budker[1,2]

[1]*Department of Physics, University of California, Berkeley, CA 94720-7300, USA*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 93420, USA*

Atomic magnetometers using ultra-narrow resonances based on coherences between Zeeman sublevels in alkali atoms, have been under development since the 1960s . Their high sensitivity makes them a possible alternative to SQUIDS without requiring the use of cryogenic equipment. While recent efforts have been dedicated to working in a magnetically shielded environment where the magnetic field can be tightly controlled, renewed interest in magnetometry in an unshielded environment leads to other challenges because of the fluctuations in the Earth magnetic field [1].

We will present experimental results on the performance of an all-optical self-oscillating atomic magnetometer/gradiometer based on alignment coherences operating at Earth magnetic field in an unshielded environment[2]. Our magnetometer combines amplitude modulated non-linear optical rotation (AM NMOR) and separate pump and probe beams. Its features are high projected sensitivity and wide bandwidth. Potential future applications range from geophysics to biomagnetic measurements in the field, and may serve as the basis of devices used in air- and space-borne platforms.

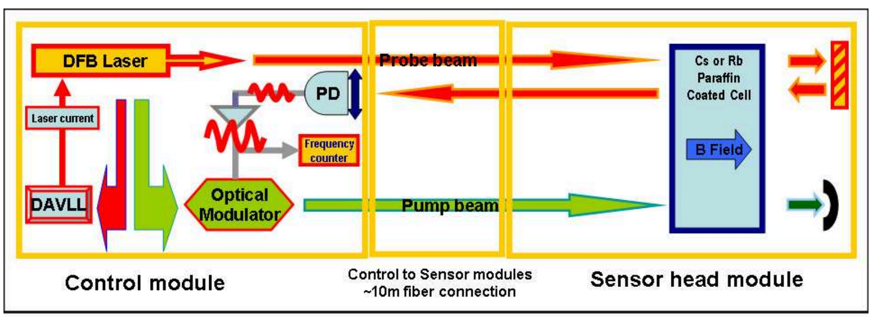

Figure 1: *-Magnetometer configuration (single sensor),*
-DAVLL: Dichroic Atomic Vapor Laser Lock,
-DFB: Distributed Feed Back laser,
-PD: Photo Diodes.

[1]D. Budker, M.V. Romalis, Nature Physics, **Vol. 3, p.227-334, April 2007**
[2]J.M. Higbie, E Corsini and D Budker, Rev. Sci. Instrum. **77, 113106 (2006)**

High-duty cycle magnetometry with cold atoms in dark optical tweezers

M. L. Terraciano, M. Bashkansky, F. K. Fatemi

Optical Sciences Division, Naval Research Laboratory, Washington, DC

Dark optical traps for cold atoms are useful for precision measurements because they provide deep potentials with reduced perturbations and low trap laser power requirements. We have used blue-detuned, high charge number hollow laser beams to confine ^{87}Rb for magnetometry and Faraday spectroscopy. The hollow laser beams are crossed in a bowtie configuration, forming a deep (300μK), large volume (0.1mm^3), box-like potential using only 200mW of laser power detuned 0.2 nm from resonance.

Magnetic field measurements are made by optically pumping the atom sample to a stretched magnetic sublevel. The subsequent Larmor spin precession, proportional to the magnetic field strength, is monitored by measuring the magneto-optic polarization rotation of a linearly polarized probe beam. The trap is sufficiently deep to make several hundred measurements of the magnetic field without reloading the trap (Fig. 1). Such measurements provide a real-time monitor of the magnetic field. We have used the precession signals to measure and compensate time-varying magnetic fields to within 10 nT over a 400 ms time window[1]. We discuss optical properties of the traps and limits to the interrogation time.

By dynamically scanning the crossed hollow beams[2], we can quickly sample the magnetic field over an extended length. We discuss our work to make multiple measurements over several millimeters in a single loading cycle to provide both high spatial and temporal resolution of the magnetic field.

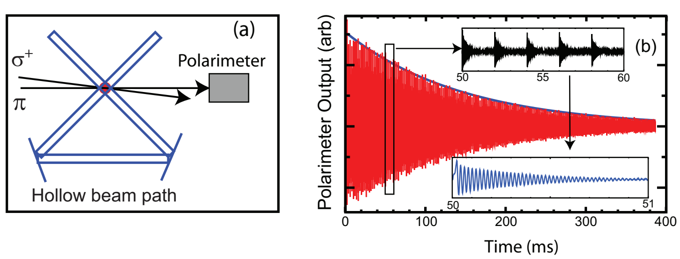

Figure 1: *a) Hollow beam layout. b) Larmor precession signals over 400 ms at a 500 Hz sampling rate. Figures adapted from Ref. 1.*

[1]M. L. Terraciano, M. Bashkansky, and F. K. Fatemi, Phys. Rev. A **77** 063417 (2008)
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Magneto-optical Resonances in Atomic Rubidium in Ordinary and Extremely Thin Cells

M. Auzinsh[1], R. Ferber[1], F. Gahbauer[1], A. Jarmola[1], L. Kalvans[1], A. Papoyan[2], D. Sarkisyan[2]

[1]*Laser Centre,University of Latvia, 19 Rainis Boulevard, LV-1586 Riga, Latvia*
[2]*Institute for Physical Research, NAS of Armenia, Astarak-0203, Armenia*

We present the results of an experimental and theoretical investigation of nonlinear magneto-optical resonances in atomic rubidium in an extremely thin vapor cells (ETCs) and an ordinary cell. Magneto-optical resonances can be bright or dark, depending on which hyperfine transition is excited. Although these sub-natural linewidth resonances have been known for some time [1], recent studies have shown that their characteristics can change in dramatic ways in ETCs. For example, it was reported that the Cs $6S_{1/2}$ $F_g = 3 \rightarrow F_g = 4$ transition appears dark in an ETC, even though it is bright in an ordinary vapor cell [2]. ETCs have the useful property that they allow sub-Doppler spectroscopy [3]. Thus, hyperfine transitions that are unresolved in ordinary cells can be resolved in ETCs. One would therefore expect that magneto-optical resonances would be easier to interpret in ETCs. However, it appears that new effects have to be taken into account. It has been suggested that collisions with the walls of the ETC depolarize the excited state and thus change the course of the optical pumping processes that lead to bright or dark resonances [3]. To test such theories and to further understand how Doppler broadening, relaxation time, and other effects influence the shape and contrast of the resonances, we compare results from ETCs with those from ordinary cells and from detailed calculations. In our experiment, we use Rubidium vapor in an ETC of thickness L between 150 nm and 1600 nm. The polarization of the exciting laser radiation is perpendicular to the magnetic field, which was scanned, and the fluorescence is observed in the direction along the magnetic field. In order to test how well our model can describe ETC behavior, we study resonances at different laser powers, beam diameters, and wall separations L in both an ETC and an ordinary cell. The experimental results are compared to theoretical calculations based on the optical Bloch equations, which have proven to be well suited to describe the signals obtained in ordinary vapor cells [4]. By requiring the model to take into account a variety of different parameters, it will be possible to understand any new effects that should be taken into account when modelling magneto-optical resonances in ETCs.

We acknowledge support from the Latvian National Research Programme in Material Sciences Grant No. 1-23/50, the University of Latvia grant Y2-ZP04-100, the ERAF grant VPD1/ERAF/CFLA/05/APK/2.5.1./000035/018, and the INTAS projects 06-1000017-9001 and 06-1000024-9075. A. J., F. G., and L. K. acknowledge support from the ESF project.

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[2]C. Andreeva et al. Phys. Rev. A 76 063804 (2007)
[3]D. Sarkisyan et al., Opt. Commun. 200, 201 (2001)
[4]M. Auzinsh et al. arXiv:0803.0201v1 [physics.atom-ph]

Error estimation for the generalized Dykhne-Davis-Pechukas approach

G. S. Vasilev[1] S. Guerin[2], H. R. Jauslin[2]

[1]*Department of Physics, Sofia University, James Bourchier 5 Boulevard, 1164 Sofia, Bulgaria*
[2]*Laboratoire de Physique, UMR CNRS 5027, Universite de Bourgogne, Boite Postale 47870, 21078 Dijon, France*

This work presents an analytic results related to the Dykhne-Davis-Pechukas approach in the case of more than one transition points situated on different Stokes lines. Davis and Pechukas [1] have suggested a generalization to include the contributions from all zero points lying on the lowest Stokes line (the closest one to the real axis) in a coherent sum. This suggestion was later verified by Joye [2]. Although not rigorously proved, Suominen [3] has shown that for the Demkov- Kunike models the full summation, involving infinitely many transition points, leads to the exact result as for the Landau-Zener model. We present a rigorous result for the full summation of all transition points. According to the geometry of the Stokes lines, we show that the generalized Dykhne-Davis-Pechukas approach provides correct asymptotic probability for nonadiabatic transitions even when there are some singularities of the quasienergy splitting, as for the Rosen-Zener model.

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Controlling ultracold Rydberg atoms in the quantum regime

B. Hezel[1], I. Lesanovsky[2], P. Schmelcher[1,3]

[1] *Physikalisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany*
[2] *Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
[3] *Theoretische Chemie, Physikalisch–Chemisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany*

The large size of Rydberg atoms affects their coupling to the inhomogeneous magnetic field of a common Ioffe-Pritchard trap and necessitates a two-body treatment. An analysis of the fully quantized center of mass and electronic states reveals that very tight confinement of the center of mass motion in two dimensions is achievable while barely changing the electronic structure compared to the field free case. [1] This provides a prerequisite for generating a one-dimensional ultracold Rydberg gas. [2]

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F-Resolved Magneto-optical Resonances in Atomic Cesium at D1 Excitation

M. Auzinsh, R. Ferber, F. Gahbauer, A. Jarmola, L. Kalvans

Laser Centre, University of Latvia, 19 Rainis Boulevard, LV-1586 Riga, Latvia

We present the results of a detailed experimental and theoretical investigation of bright and dark nonlinear magneto-optical resonances at D1 excitation of atomic cesium in an ordinary vapor cell. Although these effects have been known for some time [1], discrepancies continued to exist between theoretically predicted [2] and experimentally observed [3] behavior. One reason was that, because of Doppler broadening, several hyperfine levels contributed simultaneously to the signals in the systems that were studied previously. To clarify the discrepancies in the literature, a system in which each hyperfine transition could be studied separately was desirable. The Cesium D1 line met this requirement because the separation between the different hyperfine levels exceeds the Doppler width. At the same time, in an ordinary vapor cell, these magneto-optical resonances have widths that are less than the natural linewidth.

In our experiment, cesium atoms were excited by linearly polarized laser radiation with its polarization vector perpendicular to the magnetic field, which was scanned across zero. Laser induced fluorescence was observed along the magnetic field direction. Resonances appeared at zero magnetic field. Signals were obtained for various beam diameters, which are related to transit relaxation time, and laser power densities. The experimentally obtained signals were compared to the results of a theoretical calculation based on the optical Bloch equations, which averaged over the Doppler contour of the absorption line and accounted for the contribution of all hyperfine levels as well as mixing of magnetic sublevels in an external magnetic field. Agreement between experiment and theory was excellent and supported the traditional theoretical interpretation, which attributed these effects to optical pumping and to the relative strengths of transition probabilities between different magnetic sublevels in a given hyperfine transition. This theoretical model is now being applied to understand these effects in Extremely Thin Cells [4] of nanometric dimensions, which are interesting because they allow sub-Doppler spectroscopy and thus make it possible to study more closely spaced hyperfine transitions individually.

This work was supported in part by the Latvian National Research Programme in Material Sciences Grant No. 1-23/50, the University of Latvia grant Y2-ZP04-100, the ERAF grant VPD1/ERAF/CFLA/05/APK/2.5.1./000035/018, and the INTAS projects 06-1000017-9001 and 06-1000024-9075. A. J., F. G., and L. K. acknowledge support from the ESF project.

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[4] D. Sarkisyan et al., Opt. Commun. 200, 201 (2001)

Outcoupling of Cold Atoms by Finite-line-width Radio Frequency Field

K. Härkönen, O. Vainio, K.-A. Suominen

Department of Physics, University of Turku, FI-20014 Turku, Finland

By use of an rf-field it is possible to couple different Zeeman sublevels of an atomic gas sample. In an inhomogeneous magnetic field only certain sublevels are trapped. Therefore, atoms which are driven by a weak outcoupling field from a trapped into an untrapped $M_F = 0$ state fall freely under gravity. This coherent beam of atoms emitted from the source of cold trapped atomic cloud is referred to as atom laser[1]. Using simultaneously multiple different rf-frequencies one can create a set of atomic beams originating from spatially different resonance points. Because of the coherence properties, these beams interfere with each other, which can be observed as a beat mode in the density amplitude[2].

We present a simple yet realistic model for such outcoupling scenario using wave packet techniques arising from a finite line width of the coupling. Furthermore, our approach gives a natural interpretation for the classically intuitive event of free fall of atoms, while being consistent with the quantum mechanical description.

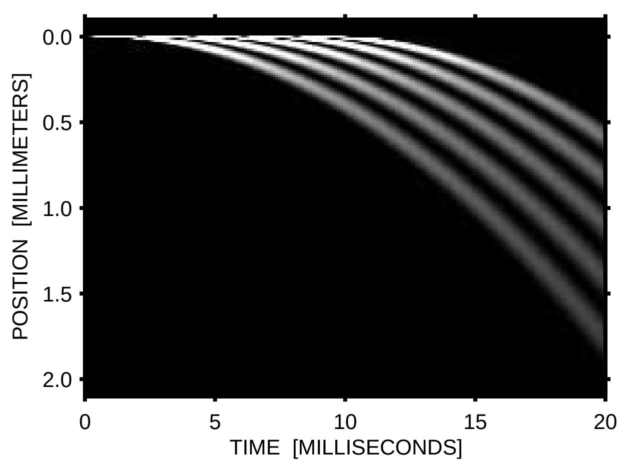

Figure 1: *Analytical wave packet result for the density profile of two interfering atomic beams outcoupled from a trap at the origin. Frequency difference of the coupling pulses is 500 Hz, and the pulse duration is 10 ms.*

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Fractional resonances of the δ-kicked accelerator

Mark Saunders[1], Paul L. Halkyard[1], Katharine J. Challis[2], Simon A. Gardiner[1]

[1]*Department of Physics, Durham University,*
Rochester Building, South Road, Durham DH1 3LE, United Kingdom
[2]*Lundbeck Foundation Theoretical Center for Quantum System Research,*
Department of Physics and Astronomy, University of Aarhus, DK-8000 Århus C, Denmark

We consider the resonant dynamics in a dilute atomic gas, falling under gravity through a periodically pulsed, standing-wave laser field. This atom-optical realisation of the quantum δ-kicked accelerator generalises our study into the effect of temperature upon quantum resonance and antiresonance[1]. Modifying the laser potential to a walking-wave allows the acceleration experienced by the atoms to be tuned. We observe fractional resonances, with the temperature dependence shown in Figs. 1(a)–(c). We explore the transition between temperature extremes by investigating the evolution of the individual quasimomentum eigenstates [Fig. 1(d)]. Changing the acceleration reveals a rich structure of resonant phenomena [Fig. 1(e)][2].

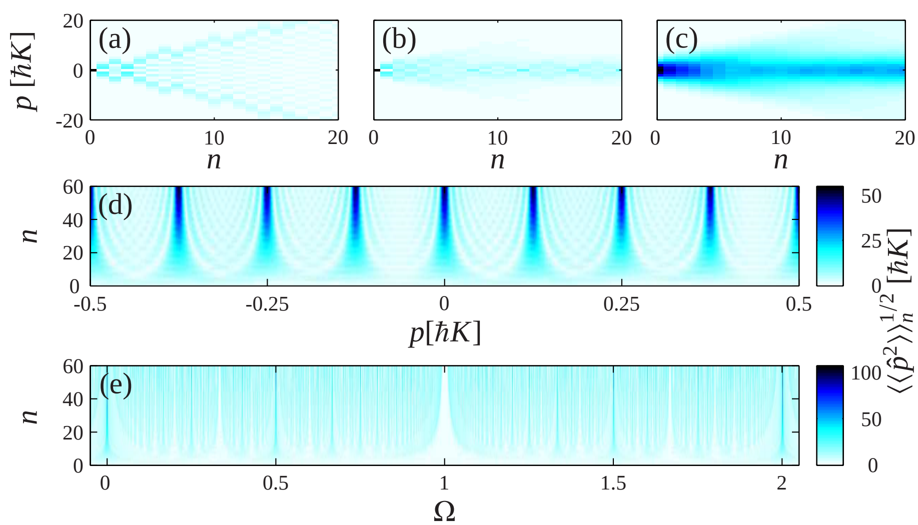

Figure 1: *The atom-optical δ-kicked accelerator, for an atom cloud with initial momentum distribution of standard deviation $w\ \hbar K$: (a) in the ultra-cold limit ($w = 2^{-10}$); (b) at an intermediate temperature ($w = 2^{-3}$); (c) in the thermal limit ($w = 2.5$), for a fourth-order resonance (setting effective acceleration parameter, $\Omega = 1/4$). The distributions are analysed by their standard deviation: (d) over the quasimomentum range, for $\Omega = 1/4$; and (e) over Ω for the $|p = 0\rangle$ subspace. Gravitational acceleration is incorporated into Ω.*

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[2] Saunders, Halkyard, Challis and Gardiner, *in progress* (July 2008)

One-Dimensional Rydberg Gas in a Magnetoelectric Trap

M. Mayle[1], B. Hezel[2], I. Lesanovsky[3], P. Schmelcher[1,2]

[1]*Theoretische Chemie, Physikalisch–Chemisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany*
[2]*Physikalisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany*
[3]*Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*

We discuss the quantum properties of ultracold Rydberg atoms in a magnetic Ioffe-Pritchard trap which is superimposed by a homogeneous electric field. The magnetic Ioffe-Pritchard trap as the basic ingredient of our setup allows very tight confinement of the center of mass motion in two dimensions while the electronic structure is barely changed compared to the field free case [1] [2]. This paves the way for generating a one-dimensional ultracold Rydberg gas by superimposing the magnetic Ioffe-Pritchard trap with an additional homogeneous electric field: Tightly trapped Rydberg atoms can thus be created in long-lived electronic states exhibiting a <u>permanent</u> electric dipole moment of several hundred Debye. The resulting dipole-dipole interaction in conjunction with the radial confinement is then demonstrated to give rise to an effectively one-dimensional ultracold Rydberg gas with a macroscopic interparticle distance[3]. Moreover, analytical expressions for the electric dipole moment and the required linear density of Rydberg atoms are derived.

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Optical field Induced Faraday Rotation at Geophysical Magnetic fields: Role of Electromagnetically Induced Transparency

M. Ummal Momeen, G. Rangarajan, P. C. Deshmukh

Department of Physics, Indian Institute of Technology- Madras, Chennai- 600 036, India.

In recent years there has been a significant interest in the study of electromagnetically induced transparency (EIT) in the presence of relatively high magnetic fields ($\sim$50G) and optical field induced Faraday rotation[1 2 3]. We examine the coexistence of EIT and Faraday rotation at geophysical magnetic fields. In the present paper, we report optical field induced Faraday rotation in ^{85}Rb and ^{87}Rb D_2 lines by realizing a system. Weak probe and strong coupling fields have been derived from two external cavity diode lasers. The measurements were performed using paraffin coated and uncoated rubidium vapour cells at room temperature. An analysis of the line shapes observed in the experiments done with paraffin coated, and uncoated, vapour cells has enabled us to assess the importance of ground state coherence. The Doppler- broadened line shape is analysed as a function of probe laser detuning for different magnetic fields. The line shape changes drastically when a magnetic field of the order of a few mG is applied, which is due to the effect of EIT on Faraday rotation.

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A multichannel second-order gradiometer for cardiomagnetic field imaging

N. Castagna[1], G. Bison[2], A. Hofer[1], P. Knowles[1], C. Macchione[1], J. L. Schenker[1], A. Weis[1]

[1] *Department of Physics, University of Fribourg, Fribourg, Switzerland*
[2] *Biomagnetisches Zentrum, Universitätsklinikum Jena, Germany*

We present the status of our optical multichannel magnetometer used to map the beating human heart. Although SQUID-based devices already make such measurements in a few medical centers worldwide, the search for a new measurement method is motivated by the high cost of the LHe cooling SQUIDs require. In our atomic Cs magnetometers, a signal indicating the local magnetic field is generated by the combined interaction of resonant optical pumping (using circularly polarized D_1 light) and magnetic resonance among the 6S $F{=}4$ Zeeman levels. Cs vapor is confined in a room-temperature, evacuated, 30 mm diameter paraffin-coated Pyrex cell, produced by us. Intrinsic cell sensitivities are individually measured and are in the range 10–25 fT$/\sqrt{\text{Hz}}$. A compact array of cells allows multichannel heart field measurements with spatial resolution of 50 mm.
The optical magnetometer array operates in an Al shielded environment, with earth-field cancellation coils, however, the measurement performance is limited by external magnetic noise. A second-order gradiometer arrangement permits direct feedback compensating linear gradient variations of the external field. Currently, fully digital FPGA (Field Programmable Gate Array) electronics drive an eight-sensor array, with six measurement channels and two reference sensors for the second-order gradiometer. We can map a 30×40 cm area (36 points) above the chest in 15 minutes, a time much shorter compared to our first apparatus[1]. Figure 1 shows typical signals (80 trace average) detected by three sensors located above the chest of a healthy adult.

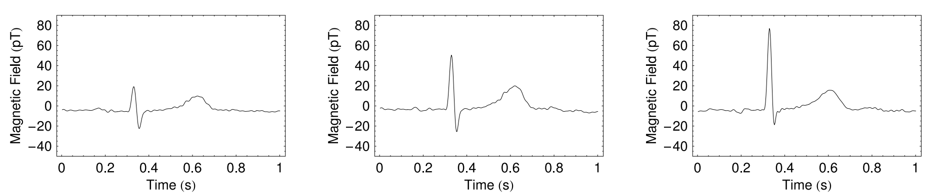

Figure 1: *Simultaneously recorded human magnetocardiogram signals measured at 50 mm separation using second-order gradiometers.*

By the end of 2008, we will operate a 25-channel second-order gradiometer array whose 19 simultaneous measurement channels will be able to reduce the acquisition time for a full heart map to only a few minutes. This optical magnetometer technology promises to be more affordable for hospitals, and hence of interest for diagnosing heart disease.
Funded by the Velux Foundation, and the Swiss National Science Foundation.

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Nonlinear Faraday Effect for magnetometric applications

S. Pustelny, A. Wojciechowski, M. Kotyrba, J. Zachorowski, W. Gawlik

Center for Magneto-Optical Research, M. Smoluchowski Institute of Physics, Jagiellonian University. 30-059 Kraków, Poland

Modern optical magnetometers reach the sensitivity comparable with, or even exceeding that of SQUIDs and find many spectacular applications[1]. Nonlinear Faraday Effect (NFE) is one of the magneto-optical phenomena that find its use in sensitive magnetometry. It is based on light-intensity-dependent rotation of the polarization plane of linearly polarized light propagating through a medium placed in a magnetic field. The rotation results from light-induced long-lived quantum superpositions of Zeeman sublevels of atomic ground state. Under special conditions, ultra-narrow resonances ($\sim 10^{-11}$ T) are observed. The resonances allow measuring very weak magnetic fields with the sensitivity reaching 10^{-15} T/Hz$^{1/2}$ [2].

We report on our approach to optical magnetometry based on NFE aiming at extending the dynamic range without compromising on high sensitivity. Application of light intensity modulation leads to appearance of additional resonances at much stronger fields (Fig.1a). The extra resonances have their positions strictly determined by the modulation frequency and hence they can be shifted to the fields of desired values. This significantly expands the range of our magnetometer which is now bigger than those of other optical magnetometers. With the field-tracking algorithm, we demonstrate the ability of tracking static or slowly varying magnetic fields in a wide range (see Fig.1b). With the non-optimized setup we show sensitivity of about 4×10^{-13} T/Hz$^{1/2}$ in a dynamic range of about 7.5×10^{-6} T [3]. We also discuss prospects of the technique for practical applications.

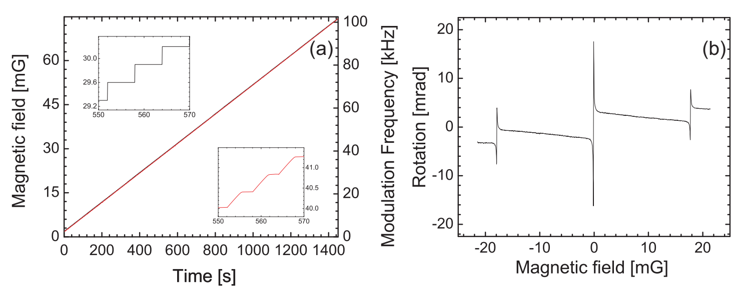

Figure 1: *(a) Signals of NFE with amplitude-modulated light. (b) Tracking of magnetic field with the NFE magnetometer. Every 9 s magnetic field was increased by* 15×10^{-9} *T. The inset blowout the magnetic field steps and the resulting frequency response.*

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Precision Computation of High Resoloving Spectrum Near Ionization Threshold

Xiang Gao[1], Shao-Hao Chen[2], Jia-Ming Li[1,2]

[1]*Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Key Laboratory of Atomic and Molecular Nanosciences of Education Ministry, Department of Physics, Tsinghua University, Beijing 100084, China*

A new method is proposed to describe quantum dynamical processes in finite space by using of a set of discretized complete basis. In this method, the finite space complete basis were obtained by solving self-consistent field equation with reflecting boundary conditions. Such method can be used in systems with non-separable Hamiltonians, eg. atoms in strong magnetic field, and time dependent dynamical problems, eg. atoms in high intensity laser field. To illustrate the validity of the method, we will present in the poster two examples: the theoretical calculation of high excited states spectrums including continuum of Barium and Sodium.
We have calculated the spectrum of high excited states including continuum for Barium from $6s^2$ to $6snp/6s\varepsilon p$ channel. In order to achieve the experimental resolution[1], ie. 0.3cm^{-1}(FWHM), we choose a large space size of 25000 bohr. The calculated optical oscillator strength is folded with a normalized Gaussian function with the experimental line width. As shown in Fig. 1, our calculated result has the same features as experimental one[1]. The measured oscillator strength converges to oscillator strength densities near the threshold and extends smoothly to continuum region.
We have also calculated a complete spectrum of optical oscillator strength densities of Sodium for dipole transitions from $3s$ state to final states of p channel, including infinite Rydberg series and adjacent continuum states. As shown in Fig. 2, the calculated result is in agreement with experimental results[2,3] below the well known Cooper-minima. The position of the Cooper-minima is in good agreement with experimental results. The difference between the experimental and theoretical result above the Cooper-minima has been discussed in detail in our earlier works[4,5].
As a summary, we can use the finite space complete basis method to do precision computation of the high excited states spectrums including continuum. Further more, using the same basis, we can solve the magnetic field problems by adding the diamagnetic matrix elements. We can also generate the Green’s function of the systems using this basis to solve time dependent dynamical problems.

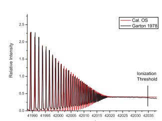
Fig. 1

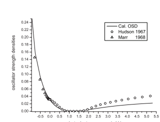
Fig. 2

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Efficient broadband de-excitation of Rydberg atoms with half-cycle pulses

P. K. Mandal, K. Afrousheh, A. Speck

The Rowland Institute at Harvard, Harvard University, Cambridge, MA 02142, USA

We report on progress towards demonstrating population redistribution of Rydberg atoms using a train of unipolar terahertz bandwidth pulses (half-cycle pulses) as initially proposed by Hu and Collins[1]. In principle this broadband technique should allow for the efficient de-excitation of antihydrogen atoms from the currently produced mix of excited states to the ground state which is a necessary prerequisite for a CPT comparison with hydrogen[2].

To produce a train of unipolar pulses with pulse widths shorter than the 10 ps orbit period of an atom in $n \approx 40$ and with a repetition rate allowing for many pulses within the lifetime of an optically excited atom ($\tau \approx 75\mu\mathrm{s}$), we have developed and characterized a system based on GaAs photoconductive switches pumped by a femtosecond oscillator. In this technique, the GaAs wafer is biased using aluminum electrodes produced using photolithography. When carriers in the wafer are then excited by the femtosecond pulse they are accelerated by the electric field and radiate a short pulse. Due to the asymmetry between excitation by a short pulse and the long carrier lifetime of semi-insulation GaAs, the radiated field is primarily unipolar. For the final experiment, a cloud of ultracold $^{85}\mathrm{Rb}$ atoms are then excited to a Rydberg state, allowed to interact with the 80 MHz pulse train of half-cycle pulses, and the final state distribution is measured as a function of the pulse train parameters.

Initial demonstrations of the techniques used for the generation of half-cycle pulses and Rydberg atom production will be described. We will also report on further developments of novel techniques utilizing the unipolar magnetic field of the half-cycle pulse. These are useful both for probing magnetic systems as well as for terahertz radiation detectors.

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[2] G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, et al., "Driven Production of Cold Antihydrogen and the First Measured Distribution of Antihydrogen States," *Physical Review Letters* **89**, 233401 (2002).

Magnetic interactions of cold atoms with anisotropic conductors

T. David[1], Y. Japha[1], V. Dikovsky[1], R. Salem[1], C. Henkel[2], R. Folman[1]

[1]*Department of Physics, Ben-Gurion Universityof the Negev, Beér Sheva, Israel*
[2]*Institut für Physik, Universität Potsdam, Potsdam, Germany*

We analyze atom-surface magnetic interactions on atom chips where the magnetic trapping potentials are produced by current carrying wires made of electrically anisotropic materials. We discuss a theory for time dependent fluctuations of the magnetic potential, arising from thermal noise originating from the surface. It is shown that using materials with a large electrical anisotropy results in a considerable reduction of heating and decoherence rates of ultra-cold atoms trapped near the surface, of up to several orders of magnitde. The trap loss rate due to spin flips is expected to be significantly reduced upon cooling the surface to low temperatures. In addition, the electrical anisotropy significantly suppresses the amplitude of static spatial potential corrugations due to current scattering within imperfect wires. Also the shape of the corrugation pattern depends on the electrical anisotropy: the preferred angle of the scattered current wave fronts can be varied over a wide range. Materials, fabrication, and experimental issues are discussed, and specific candidate materials are suggested.

Level-crossing transition between mixed states

B. T. Torosov[1], N. V. Vitanov[1,2]

[1]*Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria*
[2]*Institute of Solid State Physics, Bulgarian Academy of Sciences, Tsarigradsko chaussée 72, 1784 Sofia, Bulgaria*

The Landau-Zener model[1,2] is conventionally used for estimating transition probabilities in the presence of crossing levels. Nevertheless, because of the infinite duration of the coupling in this model, the propagator involves a divergent phase. It has been shown that this phase causes undefined populations in the degenerate Landau-Zener model[3]. In this work we show that even in the original Landau-Zener model we have undefined populations when we deal with pure superposition states or with mixed states. We show that the Allen-Eberly model[4] can be used as an alternative to the Landau-Zener model to describe the dynamics of such level-crossing problems[5].

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Dark dynamic acousto-optic ring lattices for cold atoms

N. Houston, E. Riis, A. S. Arnold

SUPA, Dept. of Physics, University of Strathclyde, Glasgow G4 0NG, UK

We propose a straightforward method for the generation of dynamic dark optical ring lattices, without requiring Laguerre-Gauss beams, spatial light modulators, large optical coherence lengths or interferometric stability. Simple control signals allow these lattices to be reproducibly rotated about the beam axis and spatially modulated, offering manifold possibilities for the creation of complex dynamic lattices. We demonstrate the optical realization of these ring lattices as rastered 2D intensity distributions from a single laser beam, which, in conjunction with a magnetic trap, will enable precision trapping and manipulation of ultracold species using blue-detuned light. The technique is ideal for azimuthal ratchet, Mott insulator and persistent current experiments with quantum degenerate gases. We compare and contrast our scheme to other related techniques.[1] [2]

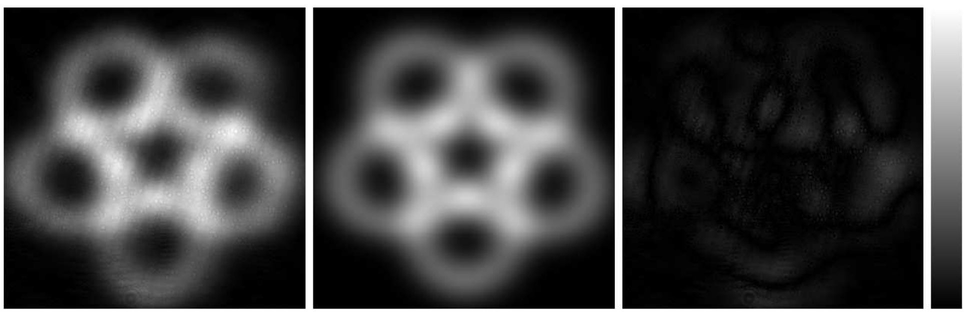

Figure 1: *Experimental relative intensity distribution (area ≈ $(4\,mm)^2$, exposure 1ms), corresponding least-squares theoretical fit and fit residue. See Ref.* [3] *for optical lattice movies comparing experimental and theoretical rotation and amplitude modulation.*

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Non-equilibrium quantum dynamics of bosonic atoms in an optical lattice

A. D. Martin, J. Ruostekoski

School of Mathematics, University of Southampton, SO17 1BJ Southampton, United Kingdom

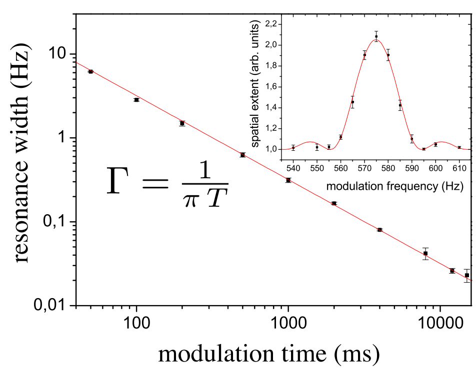
We study the effect of quantum and thermal fluctuations on bosonic atom dynamics in optical lattices within the truncated Wigner approximation in a shallow, strongly confined 1D optical lattice. This provides means to investigate the validity of the classical Gross-Pitaevskii equation in optical lattices. We study the loss of the phase coherence of atoms along the lattice, and the reduced atom number fluctuations in individual lattice sites. We also address dynamical quantum state preparation methods in such systems.

Coherent delocalization of matter waves in driven lattice potentials: a new tool to engineer quantum transport over macroscopic distances

A. Alberti, V. Ivanov, G. M. Tino, G. Ferrari

Dipartimento di Fisica and LENS - Università di Firenze, CNR-INFM, INFN - Sezione di Firenze, via Sansone 1, 50019 Sesto Fiorentino, Italy

We present the first experimental demonstration of the Wannier-Stark intraband transitions and their application to the control of quantum transport in lattice potentials. Atomic wave packets loaded into a phase-modulated vertical optical-lattice potential exhibit a coherent delocalization dynamics arising from intraband transitions among Wannier-Stark levels. Wannier-Stark intraband transitions are here observed by monitoring the in situ wave-packet extent. By varying the modulation frequency, we find resonances at integer multiples of the Bloch frequency and the resonances show a Fourier-limited width for interrogation times up to 15 s[1] (left figure). Under non-resonant driving of the lattice phase we coherently control the spatial extent of the wavefunction by reversibly stretching and shrinking the wavefunction over a millimeter distance[2] (right figure). The remarkable experimental simplicity of the scheme would ease applications in the field of quantum transport and quantum computing. We also found that the resonant tunneling process at the basis of the Wannier-Stark intraband transitions can be used to determine the gravity acceleration with sub-ppm sensitivity and sub-millimeter spatial resolution.



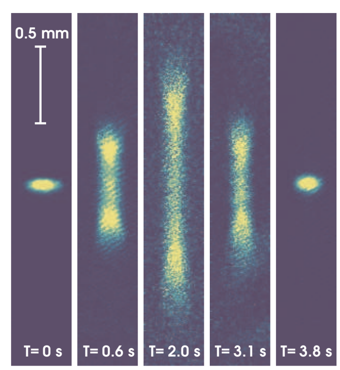


Figure 1: *Left: resonance width* Γ *(see also inset) VS the modulation time T. The line corresponds to the expected Fourier limit. Right: reversible stretching of the atomic distribution under non-resonant driving*

[1] "Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials" V. V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, Phys. Rev. Lett. 100, 043602 (2008).

[2] "Engineering the quantum transport of atomic wavefunctions over macroscopic distances" A. Alberti, V. V. Ivanov, G. M. Tino, G. Ferrari, arXiv:0803.4069v1 [quant-ph].

Coherent Dynamics of BECs in Periodically Driven Optical Lattice

A. Zenesini[1,3], H. Lignier[1,2], D. Ciampini[1,3], O. Morsch[1,2], E. Arimondo[1,2,3]

[1]*Dipartimento di Fisica Enrico Fermi, Universitá degli Studi di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy*
[2]*CNR-INFM, Largo Pontecorvo 3, I-56127 Pisa, Italy*
[3]*CNISM Unitá di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy*

In recent years, Bose-Einstein Condensates (BECs) of ultra-cold Gases have become a versatile tool for studying many-body systems. Starting from the simple system of interacting particles in a trap, different techniques can be used to modify the system's Hamiltonian, for example by adding an optical lattice or a magnetic field.
In recent works [1] the possibility of using *d*ynamic rather than static control of the dynamics of a BEC inside an optical lattice has been demonstrated. By periodically shifting back and forth the position of an optical lattice, it is possible to coherently control the external degrees of freedom of the BEC, leading to a change in the inter-site tunneling probability. In the Bose-Hubbard model, the general Hamiltonian H can be written in terms of the on-site energy U and the tunneling rate J. The effect of the shaking is a renormalization of J depending on the strength K and the frequency ω of the driving,

$$\hat{H} = +\frac{U}{2}\sum_{j}\hat{n}_j\left(\hat{n}_j - 1\right) - J_{eff}\sum_{\langle i,j\rangle}\left(\hat{c}_i^{\dagger}\hat{c}_j + \hat{c}_j^{\dagger}\hat{c}_i\right),$$

with $J_{eff} = \mathcal{J}_0(K/\omega)J$ and $\mathcal{J}_0$ is the zero-th order Bessel Function [2].
This renormalization of J adds an additional degree of control over the system, but the complexity of the resulting (quasi-)energy spectrum of the shaken system also introduces difficulties and limits to how the system can be adiabatically prepared and coherently controlled under these circumstances. Here we present our latest experimental results regarding the coherent control and adiabatic preparation in different configurations and dimensionalities with a view to the the possibility of realizing the superfluid-Mott insulator phase transition in the driven system.

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Coherence modulation at quantum resonances of δ-kicked rotor

A. Tonyushkin[1], M. Hafezi[1], S. Wu[2], M. G. Prentiss[1]

[1] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2] *NIST, Gaithersburg, MD 20899, USA*

In recent experiments[1] we have demonstrated coherence preservation for an external state atom interferometer[2] interacting with periodic kicks delivered by an optical lattice potential. This coherence preservation manifests itself in high contrast peaks in the interferometer signal that occur when the kicking period corresponds to the quantum resonances of a quantum kicked rotor[3]. The observed resonances are accompanied by fringes on a finer time scale. The typical signal vs the normalized kicking period τ in the vicinity of quantum resonance ($\tau = \pi$) is shown in Fig. 1.

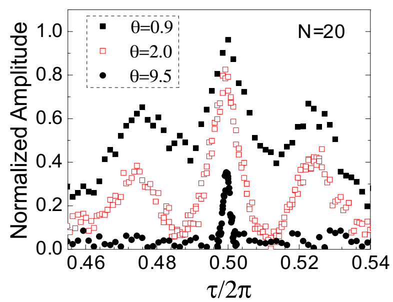

Figure 1: *Fringes at the quantum resonance (initial phase shift is 2π).*

We analyzed these fringes for high pulse areas ($\theta \sim 10$) and quasi-random perturbation regimes. We distinguish two cases depending on the initial conditions at the start of the kicks. If the delay between the interferometer pulse and first kick corresponds to π or 2π phase shifts then the fringes have a maximum at the exact quantum resonances independent of the perturbation strength θ, on the other hand, if the delay corresponds to a $\pi/2$ phase shift, fringes have local minimum at the resonance and its height depends on the perturbation strength θ. In the latter case the amplitude of the "dip" vs the number of kicks N resembles the theoretically predicted "fidelity freeze".
Our observations show an unambiguous manifestation of the interferometric nature of quantum resonances seen in previous quantum kicked rotor implementations[4]. The resonance nature and sensitivity of the observed fringes to the external potentials provides a sensitive tool for precision measurement of recoil frequency and gravity.

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Andreev-like reflections and metastable many-body states with cold atoms in optical lattices

A. J. Daley[1,2], A. Kantian[1,2], P. Törmä[3], B. Trauzettel[4], P. Zoller[1,2]

[1] *Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria*
[2] *Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria*
[3] *Department of Engineering Physics, P. O. Box 5100, 02015 Helsinki University of Technology, Helsinki, Finland*
[4] *Institute of Theoretical Physics and Astrophysics, University of Würzburg, D-97074 Würzburg, Germany*

Cold atoms in optical lattices offer clean realisations of many microscopic lattice models, with excellent control over the system parameters and a variety of techniques to measure the properties of the system. In addition, they exhibit only weak dissipative processes, resulting in long coherence times. This will allow new aspects of time-dependent coherent many-body dynamics to be probed in an experiment. Here we present two examples of how different aspects of many-body dynamics could be probed in these systems.
The first concerns making connections to phenomena predicted but not observed in mesoscopic transport systems, via observation of the propagation of an excitation through the system. We specifically look at Andreev-like reflections, or reflections of negative-density waves, which are predicted to occur in mesoscopic transport systems at boundaries where conductors with different interaction characteristics are connected (e.g., a quantum wire connected to leads). We propose a setup in which such reflections could be observed time-dependently with cold atoms in a 1D optical lattice, with a boundary engineered at which the interaction strength changes [1]. Using time-dependent DMRG methods, we calculate the transport of a density excitation with the context of the Bose-Hubbard model. We compare the resulting reflections with predictions from Luttinger liquid models, and observe strong Andreev-like reflections in experimentally attainable regimes.
In the second we investigate the formation of long lived many-body metastable states and the investigation of related quantum phases. In particular, we address systems of Atomic Lattice Excitons [2], bound metastable particle-hole pairs that are analogues of excitons in semiconductor systems, but make use of the fact that cold atoms in optical lattices provide a cleaner representation of the underlying microscopic models. Such a system would not only make it possible to observe superfluid properties of an system of excitons, but also exhibit a crystalline phase, which arises due to the large difference in tunnelling rates between atoms in different bands of an optical lattice.

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Bragg spectroscopy of cold atom gases in optical lattices

D. Clément, N. Fabbri, L. Fallani, C. Fort, M. Modugno, K. M. R. van der Stam, M. Inguscio

LENS European Laboratory for Nonlinear Spectroscopy and Dipartimento di Fisica, Università di Firenze, via Nello Carrara 1, I-50019 Sesto Fiorentino (FI), Italy.

The dynamic structure factor $S(\mathbf{q}, \omega)$ provides an important characterization of the dynamic behaviour of quantum many-body systems. In the case of gaseous Bose-Einstein condensates it provides information both on collective excitations (at low momentum transfer **q**) and on the momentum distribution (at high momentum transfer **q**) where the response is single-particle like, thus fully characterizing the excitations of the system. Bragg spectroscopy of cold atomic gases, which consists in coupling two momentum states of the same ground state by a stimulated two-photons transition, gives such a measurement of $S(\mathbf{q}, \omega)$.

The use of optical lattices with cold atomic gases has proven to be a very useful tool in the past years. It allows to change the dimensionality of these systems and study the transition from a superfluid in the presence of a lattice, where the Bloch band picture applies, to a strongly-correlated insulating state, the Mott phase. We are interested in characterizing Bose-Einstein condensates loaded in optical lattices via the measurement of their dynamic structure factor by means of Bragg spectroscopy.

We first have studied the Bragg spectra of 3D and 1D Bose-Einstein condensates in the presence of an optical lattice along the direction of the counter-propagating Bragg beams. From the measurements, we extract the resonance frequency, the width and the transition strength of the transitions to different Bloch bands of the optical lattice. We have also measured the spectra of 1D gases for different trap anisotropies, *i.e.* different Luttinger parameters. In particular, we observe an enlargement of the width of those spectra when the anisotropy increases which could be a signature of the presence of correlations.

Towards Studying Quantum Spin Systems with Ultracold Bosons in an Optical Lattice

D. Pertot[1], B. R. Gadway[1], D. Greif[1,2], R. D. Schiller[1], D. Schneble[1]

[1]*Department of Physics and Astronomy, SUNY Stony Brook, Stony Brook, NY 11794-3800, USA*
[2]*Present address: Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland*

We present our progress towards the experimental study of quantum spin systems using ultracold bosonic atoms in an optical lattice. In the limit of weak hopping, the two-component Bose-Hubbard model can be mapped to an effective spin-$\frac{1}{2}$ XXZ Heisenberg model[1,2], which can be realized, for example, by atoms of a single species in two different hyperfine states in a state-dependent optical lattice.
Our new transporter apparatus routinely produces quasi-pure ^{87}Rb Bose-Einstein condensates with up to 10^6 atoms. The movable quadrupole trap coils transport the laser-cooled atoms from the MOT to the science cell, and serve both as part of the MOT and as part of the moving-coil TOP trap (McTOP). Compared to other magnetic trap geometries, the TOP trap allows for good optical access and also is insensitive to the exact positioning of the quadrupole coils.
We avoid the atomic micro-motion intrinsic to TOP traps[3] by transferring a cold thermal cloud from the McTOP trap into a crossed optical dipole trap (XODT) at 1064 nm, where the final evaporation is performed before the optical lattice is adiabatically ramped up. The two linearly polarized XODT beams not only provide external confinement, but they can also be continuously converted into lattice beams by rotating the polarization of the retro-reflected beams relative to the incoming beams via liquid-crystal variable retarders. Together with a third, vertical lattice beam, a three-dimensional simple cubic lattice potential is formed.
We will discuss our recent experimental progress in attaining the superfluid to Mott insulator transition[4], and in creating and characterizing the $N = 1$ Mott insulator state as the starting point for our future studies.

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Observing time reversal in accelerated optical lattices dressed by amplitude modulation

A. Alberti, V. Ivanov, G. M. Tino, G. Ferrari

Dipartimento di Fisica and LENS - Università di Firenze, CNR-INFM, INFN - Sezione di Firenze, via Sansone 1, 50019 Sesto Fiorentino, Italy

Cold atoms in accelerated optical lattice potentials usually give rise to localized states, the Wannier-Stark states. Delocalization can be recovered by introducing a resonant coupling among neighboring lattice sites but so far this was demonstrated only applying a modulation to the phase of the lattice potential [1,2]. This results in the coupling at all the orders of the neighboring sites, for instance the first, the second, the third, and so on neighboring sites. On the other hand in many situations it would be preferred a pure nearest neighbor coupling to reproduce the tight binding model.

We show theoretically and experimentally that modulating the amplitude of an accelerated lattice potential at appropriate frequencies allows to implement a pure nearest neighbor coupling among the lattice sites. This gives rise to the coherent delocalization of the trapped atoms and additionally it allows to realize an exact *cosine* energy band. Taking advantage of the specific band dispersion we experimentally demonstrate the time reversal in the expansion of a thermal atomic sample trapped in the optical lattice.

We will also discuss a new measurement of possible deviations from the Newtonian gravity potential at micrometric distances based on cold atoms trapped optical lattices dressed by amplitude modulation.

[1] "Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials" V. V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, Phys. Rev. Lett. 100, 043602 (2008).

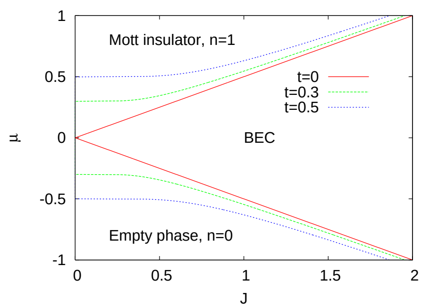
[2] "Observation of Photon-Assisted Tunneling in Optical Lattices",C. Sias, H. Lignier, Y. P. Singh, A. Zenesini, D. Ciampini, O. Morsch, and E. Arimondo, Phys. Rev. Lett. 100, 040404 (2008)

Interacting bosons in an optical lattice

O. Fialko, K. Ziegler

Institut für Physik, Universität Augsburg, Augsburg, Germany

We study a strongly-interacting Bose gas which can be treated by locally paired spin-1/2 fermions [1]. This effective fermion model is analyzed in terms of a mean-field approximation and Gaussian fluctuations. The mean-field solution gives us the phase diagram with the two merging Mott insulators and an intermediate superfluid. The effects of quantum and thermal fluctuations are investigated. Coherent and incoherent branches in the excitation spectrum are found (see Fig. 1). We also consider formation and dissociation of these paired fermionic molecules [2].



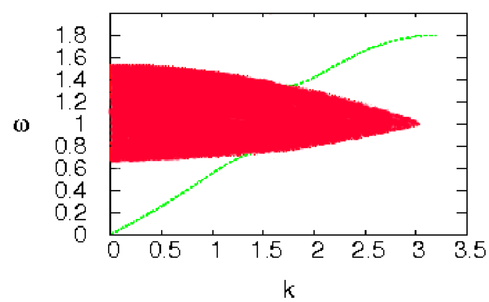


Figure 1: *Phase diagram (left) and excitation spectrum (right).*

[1] O. Fialko, Ch. Moseley and K. Ziegler, "Interacting bosons in an optical lattice: Bose-Einstein condensates and Mott insulator.", Phys. Rev. A 75, 053616 (2007).

[2] K. Ziegler, "Spin-1/2 fermions: crossover from weak to strong attractive interaction.", Laser Physics 15, No. 4, 650-655 (2005).

Staggered-vortex superfluid in an optical lattice

Andreas Hemmerich[1], Lih-King Lim[2], Cristiane Morais Smith[2]

[1]*Institut für Laser-Physik, Universität Hamburg Luruper Chaussee 149, 22761 Hamburg, Germany*
[2]*Institute for Theoretical Physics, Utrecht University, 3508 TD Utrecht, The Netherlands*

Solid state systems at low temperatures may possess exotic quantum phases, which involve order parameters with unusual symmetries. One example is the possible $d_{x^2-y^2}$-wave symmetry (staggered flux) in cuprate superconductors[1]. Can optical lattices assist to explore the realms of such quantum phases with manageable experimental complexity? As an example suggesting a positive answer, we discuss how a simple bichromatic light-shift potential can be used to apply angular momentum with alternating signs to the plaquettes of a two-dimensional square optical lattice [2]. We show that in this scenario the dynamics of cold bosonic or fermionic particles is described by a Hubbard model with an additional effective staggered magnetic field. For bosons, besides the uniform superfluid and Mott insulating phases, known from the conventional Bose-Hubbard model, the zero-temperature phase diagram exhibits a novel kind of finite-momentum superfluid phase, characterized by a quantized staggered rotational flux in each plaquette [3]. An extension for fermionic atoms, which leads to an anisotropic Dirac spectrum, may be relevant for the physics of graphene and high-T_c superconductors.

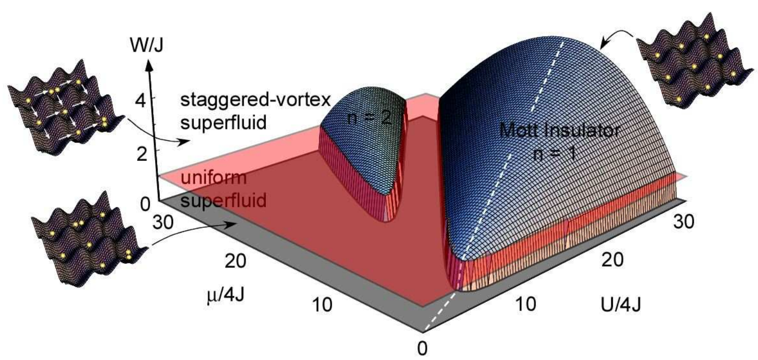


Figure 1: *Phase diagram with respect to the chemical potential μ, the interaction parameter U, the hopping amplitude J, and the scaled magnetic flux W.*

[1]I. Affleck and J. B. Marston, Phys. Rev. B **37**, 3774 (1988).
[2]A. Hemmerich and C. Morais Smith, Phys. Rev. Lett. **99**, 113002 (2007)
[3]L.-K. Lim, C. Morais Smith, and A. Hemmerich, Phys. Rev. Lett. **100**, 130402 (2008)

Mesoscopic Aspects of Strongly Interacting Cold Atoms

S. D. Huber[1,2], G. Blatter[1]

[1]*Theoretische Physik, ETH Zürich, CH-8093 Zürich, Switzerland*
[2]*Centre Emile Borel, Institut Henri Poincaré 11, rue Pierre et Marie Curie, 75005 Paris*

We investigate the heat transport in a heterostructure of trapped bosonic atoms subject to an optical lattice. At finite temperature, the exchange of heat or entropy between different superfluid shells in a wedding cake structure is exponentially suppressed with the size of the Mott layer. However, up to a critical hopping amplitude $t_\star < t_c$, smaller then the critical hopping for the bulk Mott transition, a finite undamped heat current can flow. We discuss the implication of our findings on the temperature aspects in recent experiments.

Quantum dynamics of matter wave emission in optical lattices

I. De Vega, D. Porras, J. I. Cirac

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, Garching, D-85748, Germany

In this work we show that with atoms in an optical lattice it is possible to observe a broad spectrum of different phenomena usually related to light–matter interactions. Here, the role of the matter is played by the absence/presence of one atom in the ground state of the optical potential, whereas the role of light is played by weakly–interacting atoms in a different internal state which are trapped by a different optical potential. The coupling between those two systems is induced by a laser, which simply connects the two internal states of each atom. As we will show, the Hamiltonian that describes this situation is very similar to that describing the interaction between two–level atoms and the electromagnetic field within a photonic crystal.

By changing the laser and optical trapping parameters it is possible to drive the system to different regimes where a rich variety of phenomena can be observed. These include the spontaneous polarization of the system predicted by the mean field theory, collective effects in the emission of atoms from the lattice, and the formation of a bound trapped–untrapped atom state, analogous to the atom–photon bound state that appear when atoms within a photonic crystal (PC) emit photons within the gap region. Moreover, it is possible to reach a regime in which weakly confined atoms drive atom–atom interactions between strongly confined ones, giving rise to effective Coulomb-like interactions between them.

Soliton in a lattice emerging from quantum mechanics

J. Javanainen, U. Shrestha

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

We study a soliton in an optical lattice containing bosonic atoms quantum mechanically, using both an exact numerical solution and Quantum Monte Carlo (QMC) simulations. The computation of the state is combined with an explicit theory for the measurements of the numbers of the atoms at the lattice sites. In particular, it turns out that importance sampling in the QMC method produces faithful simulations of the outcomes of individual experiments. In a lattice-translation invariant system, under circumstances when classically the ground state is a localized soliton, the quantum ground state is invariant under lattice translations and favors no particular location. Nonetheless, measurements of the positions of the atoms break the translation symmetry, and produce a localized atom distribution. Besides demonstrating our view that measurements are the agent that generates the import of nonlinear phenomena from linear quantum mechanics, this line of thought also opens up new problems. For instance, quantum fluctuations of the atom numbers in a soliton directly contradict the Bogoliubov theory.

Robust quantum phases via three-body recombination

J. M. Taylor[1], A. J. Daley[2,3], S. Diehl[2,3], P. Zoller[2,3]

[1]*Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02138, USA*
[2]*Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, A-6020 Innsbruck, Austria*
[3]*Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria*

Cold atoms in optical lattices have the potential to simulate a variety of interesting condensed matter systems. However, prior work has been limited to elastic two-body interactions and higher order, perturbative generation of three- and four-body terms, which are necessary to implement a variety of exotic quantum phases. We consider an inelastic but non-perturbative three-body interaction in optical lattice—three-body recombination—in the context of the lowest band of the Bose-Hubbard model. We find that fast recombination leads to an effective theory in which no more than two atoms are allowed per lattice site, and use this constraint to examine previously inaccessible regions of the phase diagram. We also consider the dynamic generation of novel phases such as a dimer superfluid, described in this work, by adiabatically changing interaction parameters from the well-known Mott insulator phase.

A quantum gas microscope for the simulation of condensed matter systems

J. Gillen[1,2], A. Peng[1,2], W. Bakr[1,2], S. Fölling[1,2], M. Greiner[1,2]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2]*Harvard-MIT Center for Ultracold Atoms, Cambridge, MA 02138, USA*

Ultracold atoms in optical lattices provide an exciting new opportunity to study condensed matter physics. These systems are very clean and controllable, and allow for the implementation of idealized theoretical models with high fidelity. Compared to typical real crystals, the lattice spacings of the optical potential are increased by at least three orders of magnitude, bringing optical single site addressability within reach. With such an optical resolution, imaging atoms on single lattice sites allows direct detection of quantum states such as the Mott insulator and antiferromagnetic states or excitations such as spin waves. Additionally it would enable the projection of arbitrary potential landscapes with high spatial frequency as well as efficient spatially resolved manipulation of the atomic ensemble in the trap.

We present our implementation of a quantum gas microscope to experimentally realize high resolution imaging and spatial addressability of a rubidium atom ensemble loaded into an optical lattice. Very good optical access to the atoms combined with solid immersion–like geometry is expected to provide an imaging resolution of about $0.5\,\mu$m. Due to the small depth of field, we realize a two-dimensional quantum gas inside a novel opto-magnetic surface trap using an evanescent wave potential. Despite being only $3\,\mu$m from a glass surface, the condensate exhibits lifetimes of tens of seconds and very low heating rates in this trap.

To create the lattice potential, a projection approach using holographic phase masks is developed. Here, the lattice sites are produced by projecting an intensity pattern through the microscope optics, allowing for high flexibility in the lattice geometries. In analogy to these intensity patterns, phase patterns can also be created. We apply this method to coherently transfer angular momentum to the atom cloud and to produce vortex patterns such as vortex-antivortex pairs or spin textures. Vortex patterns with arbitrary geometry can be created and are detected using a matter-wave interference technique.

Numerical study of Bose-Fermi mixtures in a 3D optical lattice based on the Gutzwiller approximation

M. Yamashita[1], M. W. Jack[2], K. Igeta[1], Y. Tokura[1]

[1]*NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan*
[2]*Scion, 49 Sala Street, Private Bag 3020, Rotorua, New Zealand*

Mixtures of bosonic and fermionic species show the novel quantum effects originated from the interplay between quantum statistics and many-body inter-particle interactions. Quite recently, K. Günter *et al.* studied the quantum phase transition of bosons from a superfluid to a Mott-insulator (MI) using a mixture of bosonic ^{87}Rb and fermionic ^{40}K atomic gases trapped in a three-dimensional optical lattice.[1] Measuring the interference patterns of time-of-flight images, they found that only 10% admixture of fermions diminishes the phase coherence of bosons, which suggests a strong correlation between both species in the mixture.

We have quantitatively analyzed these experimental results [1] on the basis of the three-dimensional Bose-Fermi Hubbard model with harmonic confinement. A highly efficient numerical method based on the Gutzwiller approximation [2] is employed to obtain the many-body ground state of large 3D systems with more than 10^5 lattice sites. Figure 1 shows the results of the average number distribution of atoms in the $y = 0$ plane assuming strongly interacting 1.2×10^5 bosons and 10^4 fermions in the system. In Fig. 1(a), due to the attractive interactions between bosons and fermions, all fermionic atoms localize around the center of lattices and form the band insulator (BI) state (i.e., $n_i = 1$). While in Fig. 1(b), the distribution of bosons is divided into two regions: the high density region around the center ($n_i \approx 5$) where bosons and fermions coexist and the outer MI region ($n_i = 1, 2$). Our calculated results quantitatively demonstrate both distributions of bosons and fermions strongly correlate with each other. We show the systematic analyses of the 3D Bose-Fermi Hubbard model and compare them with the recent experimental results.

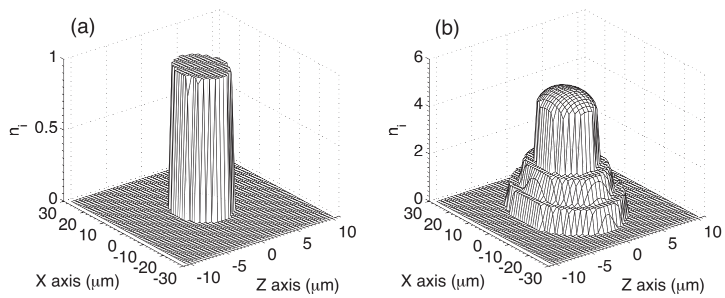


Figure 1: *Average number distribution of Bose-Fermi mixtures in a 3D optical lattice (in the y=0 plane): (a) fermions in the BI phase and (b) bosons in the MI phase.*

[1]K. Günter *et al.*, Phys. Rev. Lett. **96**, 180402 (2006).
[2]M. Yamashita and M. W. Jack, Phys. Rev. A **76** 023606 (2008).

Pump-probe spectroscopy of 1D and 2D optical lattices

M. Brzozowska, B. Baran, M. Bober, A. Wojciechowski, J. Zachorowski, W. Gawlik

M. Smoluchowski Institute of Physics, Jagiellonian University Kraków, Poland

By applying our method of pump-probe diagnostics[1] to the sample of ^{85}Rb atoms in a MOT subject to simultaneously applied optical lattice field, we perform diagnostics of atoms in various confining potentials. With non-resonant pump the diagnostics is nondestructive and can be performed in real-time yielding information on coexistence and competition of non-localized vs. localized atoms and their dynamics in various field configurations. In particular, for atoms in MOT without lattice field the pump-probe spectroscopy yields momentum distribution of atoms (recoil-induced resonances labeled as B in Fig. 1a); with an addition of a second, counter-propagating pump beam the 1D optical lattice is created and we detect additional vibrational structures associated with lattice-localized atoms (resonances V in Fig. 1b). With 2D lattice with stable relative time phases between the lattice beams[2] we see complex spectrum reflecting atomic dynamics in a potential which may have 2D node, or anti-node structure, depending on the polarization of the lattice beams. Fig.1 c depicts spectral structure for 2D lattice with E-vector of all beams in the plane defined by the lattice and probe beams. In this configuration we realize a standard topography of a lattice with potential wells in lattice nodes, but for light polarizations orthogonal to the lattice plane an interesting, anti-node structure is realized[3] which is responsible for very different pump-probe spectra.

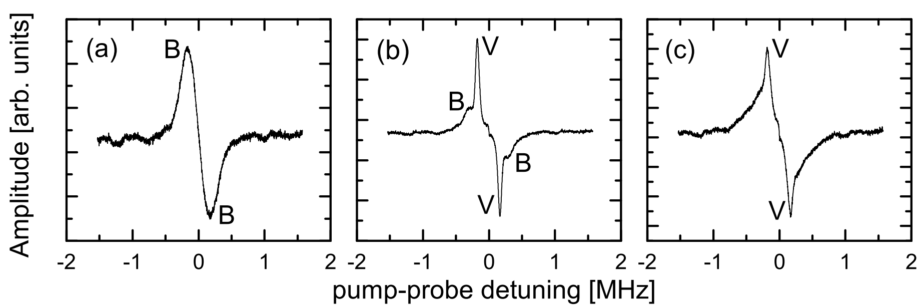


Figure 1: *Pump-probe spectra (a) without lattice field, (b) with 1D lattice, (c) with 2D lattice.*

[1] M. Brzozowska, T.M. Brzozowski, J. Zachorowski, and W. Gawlik, “Bound and free atoms diagnosed by the recoil-induced resonances: 1D optical lattice in a working MOT”, Phys. Rev. A **73**, 063414 (2006).

[2] A. Rauschenbeutel, A. Schadwinkel, V. Gomer, and D. Meschede, “Standing light fields for cold atoms with intrinsically stable and variable time phases”, Opt. Comm. **148**, 45 (1998).

[3] K.I. Petsas, C. Triché, L. Guidoni, C. Jurczak, J.-Y. Courtois and G. Grynberg, “Pinball atom dynamics in an antidot optical lattice”, Europhys. Lett. **46**, 18 (1999).

Resonant Feshbach scattering of fermions in one-dimensional optical lattices

M. Grupp, R. Walser, W. P. Schleich

Institut für Quantenphysik, Universität Ulm, Germany

We consider Feshbach scattering of fermions in an one-dimensional optical lattice [1]. By formulating the scattering theory in the crystal momentum basis, one can exploit the lattice symmetry and factorize the scattering problem in terms of center-of-mass and relative momentum in the reduced Brillouin zone scheme. Within a single band approximation, we can tune the position of a Feshbach resonance with the center-of-mass momentum due to the non-parabolic form of the energy band (see Fig. 1). We present numerical results for resonant scattering in an 1D lattice. In order to understand this results we discuss an analytic model for the coherent tunneling of atoms and dimers in half spaces.

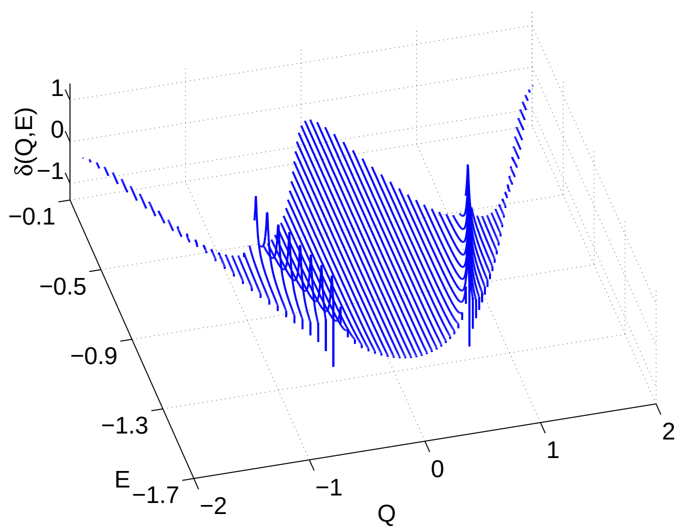


Figure 1: *Even scattering phase-shift $\delta(Q, E)$ of a two-particle Bloch-wave versus energy E and center-of-mass momentum Q. One can see clearly Feshbach resonances symmetrically located around the Q-axis, which disappears when the bound state is outside the band.*

[1] M. Grupp, R. Walser, W. P. Schleich, A. Muramatsu and M. Weitz, J. Phys. B: At. Mol. Opt. Phys. 40 (2007) 2703-2718

Self-trapping of Bose-Einstein condensates in shallow optical lattices

M. Rosenkranz[1,2], D. Jaksch[1,2], F. Y. Lim[3], W. Bao[3]

[1]*Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, UK*
[2]*Keble College, Parks Road, Oxford, OX1 3PG, UK*
[3]*Department of Mathematics and Center for Computational Science and Engineering, National University of Singapore, Singapore 117543*

For the development of possible future microdevices it is important to understand the transport properties of Bose-Einstein condensates (BECs) through guiding structures such as one-dimensional (1D) optical lattices. Such microdevices will be based on internal degrees of freedoms, the basis of spintronics[1], or indeed on the atoms themselves (atomtronics[2]).
We study, both numerically and analytically, the transport of a strongly repulsive BEC through a shallow 1D optical lattice of finite width. This system exhibits a sudden breakdown of the atomic current in the lattice at high interaction strengths. It is investigated how the drop depends on the lattice depth and the interaction strength. We attribute the sudden current drop to the development of a self-trapped state over a few lattice sites. This self-trapped state disappears after a finite time as a result of the finiteness of the lattice. Furthermore, we show that it is possible to prohibit the self-trapping by applying a constant offset potential to the lattice region. The large reduction of the current could potentially be relevant for applications of guided BECs, where the optical lattice acts as a wire between two reservoirs.

[1]S. A. Wolf et al., Science **294**, 1488 (2001)
[2]B. T. Seaman, M. Krämer, D. Z. Anderson, M. J. Holland, Phys. Rev. A **75**, 023615 (2007)

Quantum Phases and Quantum Information of Interacting Atomic Gases in Optical Lattices

C. L. Hung, X. Zhang, S. Waitukaitis, A. Sharma, K. A. Brickman, N. Gemelke, C. Chin

James Franck Institute and Department of Physics, University of Chicago, Chicago, IL 60637, USA

We describe two experiments designed to investigate quantum phases, quantum information and few-body physics using interacting ultracold ^{133}Cs and ^{6}Li atomic gases confined to optical lattice potentials.

The realization of the superfluid to Mott-insulator phase transition with neutral atoms in an optical lattice provides a tantalizing opportunity to test many-body physics with a high degree of accuracy. We report progress on an experimental and quantitative comparison of the superfluid to Mott-insulator quantum phase boundary with results from the Bose-Hubbard model, using Bose-condensed cesium atoms confined to a thin layer of an optical lattice potential. Feshbach resonances with cesium atoms enable us to scan the on-site interaction over a wide range without modifying the tunneling rate and the overall trapping potential; chemical potential can be adjusted by loading a varied mean atomic density into the lattice. We describe the physical apparatus constructed for this investigation, including novel construction designed to achieve precise and agile control of the magnetic field used in tuning interactions, adiabatic loading and manipulation of the lattice potential, and tight two-dimensional confinement applied to negate the effect of gravity without sacrifice in system homogeneity. Further, we describe precise tests of fundamental physics of interacting few-body systems possible in this apparatus.

In addition, we propose a new scheme for quantum information processing utilizing two different atomic species held in two independently controlled optical lattices. One uniformly filled lattice holds fermionic ^{6}Li atoms which act as quantum bits (qubits). A second, less densely populated, lattice holds bosonic ^{133}Cs atoms which mediate entanglement among the qubit atoms. By dynamically translating the second lattice, cesium atoms can be transported to address any lithium atom in the first lattice via contact interactions. In this way, the ^{133}Cs atoms act as quantum messengers among the ^{6}Li atoms. By using these auxiliary messenger atoms, each ^{6}Li qubit can be individually addressed, and any two of the ^{6}Li atoms in the lattice can be entangled through controlled coherent scattering with ^{133}Cs atoms. This system is inherently scalable, as a large number of qubits can be easily addressed, manipulated and transported without qualitative modification to the scheme.

Ground States of Cold Neutral Fermions in 2-Dimensional Optical Lattices: Effects of Strong Correlation in Square and Triangular Lattices

M. Okumura[1,2], S. Yamada[1,2], M. Machida[1,2]

[1]*CCSE, Japan Atomic Energy Agency, 6–9–3 Higashi-Ueno, Taito-ku, Tokyo 110–0015, Japan*
[2]*CREST (JST), 4–1–8 Honcho, Kawaguchi, Saitama 332–0012, Japan*

The Hubbard model is one of the most fundamental models in the solid state physics. In particular, the single-band Hubbard model with strong repulsive interaction in 2-dimension is a candidate to describe the high-T_c superconductivity whose mechanism has not been understood. Thus, systematic studies are desired to reveal characteristics of this model. We expect that the cold neutral fermionic system gives us a chance to do it because many parameters in this system are highly controllable, e.g., shapes of trap potential, imbalance ratio of spin population, coupling constant.
In this paper, we study ground sates of the single-band Hubbard model with repulsive interaction in various lattice and trap configurations. First, we investigate fermions in the square lattice confined by a box trap[1]. The remarkable issue in this system is a formation of bi-hole pair stripe [2] which has been predicted by Chang and Affleck[3]. To author's knowledge, this is the first confirmation of the prediction. Next, we consider the fermions in the square and triangular optical lattices confined by the harmonic potential. Generally, in this configuration, the Mott core is formed in the center of the trap[4] when the number of particles and the coupling constant are enough large. We study the spin structure of the Mott core with varying the ratio of the spin population. In the triangular trapped system, we find that the Mott core becomes a perfectly polarized core, i.e., the minority is perfectly ejected from the Mott core region, when the imbalance is in a large range. In a middle range, complex spin structures are found in the Mott core, which is not spatially homogeneous. Such a ferromagnetic Mott core and the complex spin structures are never observed in the square lattice case.

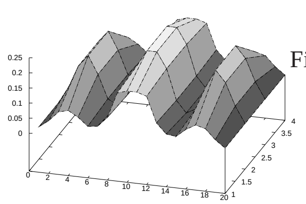


Figure 1: *The result of the hole density profile for $U/t = 5$. The number of doped holes is 8.*

[1]T. P. Meyrath, F. Schreck, J. L. Hanssen, C.-S. Chuu, and M. G. Raizen, Phys. Rev. A **71**, 041604 (2005).
[2]M. Machida, M. Okumura, and S. Yamada, Phys. Rev. A **77**, 033619 (2008).
[3]M.-S. Chang and I. Affleck, Phys. Rev. B **76**, 054521 (2007).
[4]M. Rigol and A. Muramatsu, Phys. Rev. A **69**, 053612 (2004).

Experimental demonstration of single site addressability in a 2D optical lattice with 600 nm period

T. Gericke, P. Würtz, D. Reitz, T. Langen, A. Koglbauer, H. Ott

Institute of Physics, University of Mainz, Germany

Imaging and addressing neutral atoms in the sites of an optical lattice is a prerequisite for various studies on the static and dynamic properties of ultracold quantum gases in periodic potentials. Possible applications range from real space study of tunneling phenomena over quantum simulation to applications in quantum information processing. The small lattice spacing of typically less than 1 μm has so far prevented the direct observation of single sites by optical means.

We have developed a novel microscopy technique that allows for the *in situ* detection of single atoms inside an ultracold quantum gas with a spatial resolution of better than 150 nm. It is based on scanning electron microscopy and employs the electron impact ionization of atoms with subsequent ion detection (see Fig. 1). We present high precision measurements of the density distribution of a trapped quantum gas[1] and show scanning electron microscope images of a condensate loaded in a 1D and 2D optical lattice. The individual lattice sites can be clearly resolved with high contrast and the measured density profile is in good agreement with theoretical calculations. Removing atoms from chosen sites we demonstrate single site addressability in a 2D optical lattice.

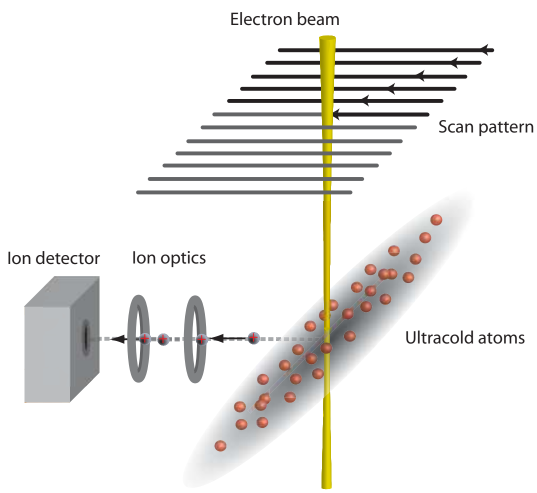


Figure 1: *Working principle of the scanning electron microscope: A focused electron beam is scanned over the cloud and ionizes the atoms which are subsequently detected with an ion detector.*

[1]T. Gericke, P. Würtz, D. Reitz, T. Langen, and H. Ott, *High resolution imaging of single atoms in a quantum gas* arXiv:0804.4788.

Asymmetric Landau-Zener tunnelling and non-exponential decay in a periodic potential

J. Radogostowicz[1], A. Zenesini[1,3], H. Lignier[1,2], C. Sias[4], D. Ciampini[1,3], M. Jona-Lasinio[5], S. Wimberger[6], O. Morsch[1,2], E. Arimondo[1,2,3]

[1]*Dipartimento di Fisica Enrico Fermi, Universitá degli Studi di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy*
[2]*CNR-INFM, Largo Pontecorvo 3, I-56127 Pisa, Italy*
[3]*CNISM Unitá di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy*
[4]*Cavendish Laboratory, University of Cambridge, Cambridge CB3B 0HE, UK*
[5]*LENS, Via N. Carrara 1, 50019 - Sesto Fiorentino, Italy*
[6]*UniversitŁt Heidelberg, Philosophenweg 19, D-69120 Heidelberg, Germany*

Landau-Zener tunnelling is a well-known phenomenon in physics and has been studied in a variety of contexts[1]. The Landau-Zener formula presents an analytical solution of the equations of motion for this transition. Here we present experimental and theoretical results on deviations from simple Landau-Zener theory obtained with Bose-Einstein condensates in accelerated optical lattices[2]. We investigated the case of Landau-Zener tunnelling in the presence of nonlinearity which led to an asymmetric tunnelling rate [3](probability of tunnelling from the lower to the upper energy band of the optical lattice is different from the probability for the opposite direction). We also studied the influence of the localisation of the BEC in momentum space on the time dependence of the survival probability in Landau-Zener tunnelling (non-exponential decay as a function of time). In the experiment with the non linear system we observed an asymmetry of Landau-Zener tunnelling. An enhancement of the Landau-Zener tunnelling probability occurs when the atoms tunnel from the lower to the upper energy band while suppression takes place in the opposite direction[4]. This asymmetry is well reproduced by a simple theoretical model taking into account the interaction between the atoms in the BEC. The non-exponential decay experiment investigated the survival probability as a function of time of a BEC initially loaded into the lowest energy band of an optical lattice. We observed deviations from the simple exponential decay curve predicted by the Landau-Zener formula; these deviations are due to the BEC localisation in momentum space. For a BEC whose momentum is well localised inside the Brillouin Zone, step-like discontinuous decay was observed. By inducing a dynamical instability in the BEC we were able to create condensates spread out in the Brillouin zone. When the BEC was no longer contained in a precise region of momentum space (i.e., the occupation area was wider) the visible steps became smoother and less evident. When the BEC filled the entire Brillouin zone, the survival probability as a function of time was again described by a simple exponential curve.

[1]C. Sias, A. Zenesini, H. Ligner, S. Wimberger, D. Ciampini, O. Morsch, E. Arimondo, Physical Letters Review, Vol 98, 120403 (2007)

[2]M. JonaLasino, O. Morsch, M. Cristiani, N. Malossi, J.H. Mller, E. Courtade, M. Andrelini, E. Arimondo, Phys. Let. Rev., Vol 91, 30406 (2003)

[3]B. Wu and Q. Niu, Physics Review A, Vol 61, 023402 (2000), J. Liu et all., ibid. 66, 023404 (2002)

[4]M. Cristiani, O. Morsch, J.H. Mller, D. Ciampini, E. Arimondo, Physical Review A, Vol 65, 063612 (2002)

Flat-top Beams for a Homogeneous Optical Lattice

J. Liang[1], R. N. Kohn Jr.[2], S. Wan[2], M. F. Becker[1], D. J. Heinzen[2]

[1]*Department of Electrical and Computer Engineering, University of Texas, Austin, TX 78712*
[2]*Department of Physics, University of Texas, Austin, TX 78712*

Experimental work using quantum gases in optical lattices has been limited by spatial inhomogeneities due to the Gaussian intensity profiles of the lattice laser beams. We have developed a laser beam-shaper that uses a digital micro-mirror device in conjunction with an iterative error diffusion algorithm to generate beams having rms intensity flatness of 0.5% over a significant portion of the beam, as shown in the figure below. Three such systems will be applied to a vacuum system containing a Bose-Einstein condensate in order to generate a homogeneous three-dimensional lattice. The homogeneous lattice will allow us to probe the superfluid-Mott insulator transition with high precision. It will avoid the problems arising from averaging over a wide range of effective chemical potentials that occur when using a lattice with large local fluctuations in depth.
Furthermore, our apparatus will allow us to custom-tailor smoothly varying optical lattice potentials for a wide variety of experimental applications. One such application would be the emerging field of atomtronics[1], in which structures analogous to common electronic devices are created by shaping the potential in which a sample of cold atoms resides.

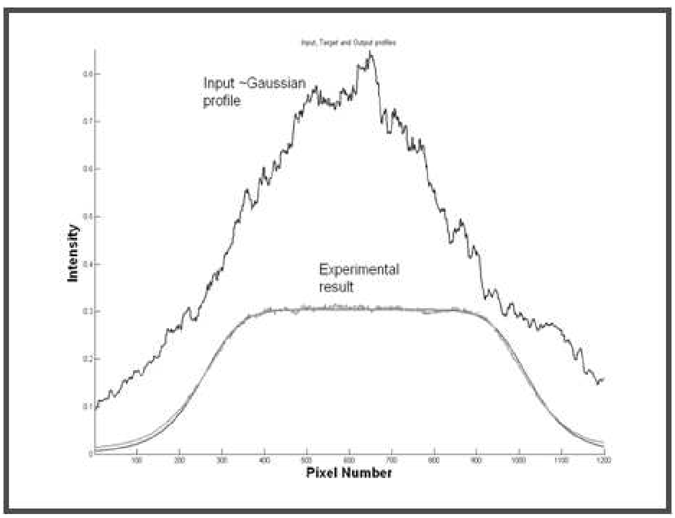


Figure 1: *Noisy Gaussian input beam is converted to output beam with RMS flatness of 0.5% over an area with a diameter of 1700 μm. The target profile, an 8th order super-Lorentzian, is plotted for comparison.*

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All-optical 3D atomic loops generated with Bessel light fields

K. Volke-Sepúlveda, R. Jáuregui

Departamento de Física Teórica, Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, México 01000 D.F. México

Circular optical lattices and helical waveguides constitute interesting alternatives for interference experiments with matter waves and quantum transport. They are based on the transfer of orbital angular momentum of light to cold atoms. Recently the use of stationary waves in the angular direction, generated by the superposition of two counter rotating Laguerre Gaussian (LG) beams propagating in the same direction, was proposed as an efficient means of achieving the exchange of angular momentum between light and cold atoms[1]. In this case, the confinement in the radial direction can be achieved optically, but the dynamics along the z axis is completely free. A circular optical potential of this kind would split the wave function of a single localized atom into clockwise and anticlockwise components, which may interfere under certain confinement conditions. On the other hand, a curved helical lattice, which could be generated by the superposition of two identical LG beams propagating in opposite directions, can also be used as an atom guide[2]. Circular and rotating optical lattices have been studied as well, in the context of condensed matter and many particle systems, such as Fermi gases and Bose Einstein condensates [3].

In this work, the propagation invariance of Bessel beams as well as their transversal structure are used to perform a comparative theoretical analysis of their effect on cold atoms for several configurations. We show that, even at temperatures for which the classical description of the atom center of mass motion is valid, the interchange of momenta, energy and orbital angular momenta between light and atoms yields efficient tools for all-optical trapping, transporting and, in general, manipulating the state of motion of cold atoms. For a red detuned far-off-resonance system, the single rotating Bessel beam and the twisted helical lattice are shown to be useful to guide atoms, in the latter case along predetermined separate channels, whereas the 3D stationary circular lattice and the toroidal train lattice can be applied to obtain 3D confinement within a small region of the space. Moreover, in the toroidal train lattice the confinement may be accompanied by a transfer of orbital angular momentum when the detuning is small. Finally, on the basis of our numerical results, we propose an application consisting of the consecutive operation of the different options of light fields in order to create atom circuits or loops in predesigned ways by all-optical means.

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Interacting Mixtures of Bosons and Fermions in an Optical Lattice

S. Will[1], Th. Best[1], U. Schneider[1], S. Braun[1], L. Hackermüller[1], I. Bloch[1]

[1] *Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany*

Mixtures of ultracold quantum gases in optical lattices form novel quantum many-body systems, whose properties are governed by the interplay of quantum statistics, inter- and intraspecies interactions, as well as the relative atom numbers of the constituents involved. In our setup, we cool bosonic ^{87}Rb and fermionic ^{40}K to simultaneous quantum degeneracy, giving us access to both Bose-Fermi and Fermi-Fermi mixtures. We study their properties in the combined potential of a blue-detuned three-dimensional optical lattice and a red-detuned crossed dipole trap, allowing for independent control of lattice depth and underlying harmonic confinement.
Bose-Fermi: We have investigated Bose-Fermi mixtures with tunable interspecies interactions in a three-dimensional lattice potential. Distinct ratios of ^{87}Rb to ^{40}K have been prepared at various lattice depths, and interspecies interactions have been tuned over a wide range using a Feshbach resonance. We have identified different regimes of the mixture through the analysis of the ^{87}Rb momentum distribution. Most prominently, we observe a remarkable asymmetry between strongly attractive and repulsive interactions, while for vanishing interactions the fermions become fully transparent for the bosons. On the attractive side, the lattice depth at which the condensate fraction vanishes, shifts towards lower values by up to 10 recoil energies. We attribute this shift to self-trapping of the bosons.
Fermi-Fermi: Spin mixtures of fermionic atoms in a three-dimensional lattice potential can serve as a model system of the Hubbard Hamiltonian. Particularly, the possible realization of a Mott-insulating state makes them highly relevant for solid state physics. We present measurements of both local and global observables on non-interacting and strongly interacting systems. Our results show the existence of conducting and insulating many-body states, and are compared to numerical simulations.

Preparing and Detecting Quantum States with Ultracold Atoms in an Optical Superlattice

S. Trotzky[1], U. Schnorrberger[1], P. Cheinet[1], M. Feld[1,2], J. D. Thompson[1], S. Fölling[1,3], I. Bloch[1]

[1] *Johannes Gutenberg Universität Mainz, Germany*
[2] *Technische Universität Kaiserslautern, Germany*
[3] *Harvard University, USA*

Ultracold atoms in optical lattices have shown to be versatile systems to mimick condensed matter physics. The concept of superlattices for ultracold atoms has recently been realized in experiments and extends the toolbox for the manipulation of the system on the many-body scale. Furthermore, it allows to control effective interactions and dynamics emerging in Hubbard-type models. In our experiments, we combine monochromatic optical lattices on two perpendicular axes with a superlattice on the third axis which is formed by the superposition of two standing light fields with periodicity d and 2d to yield an array of double well potentials. We demonstrate how this bichromatic superlattice can be used to realize effective spin Hamiltonians with controllable spin-spin interactions as well as how to measure the atomnumber distribution within the array by means of interaction blockade. Moreover, we are able to create entangled spin-triplet pairs in the double wells and detect these via the coherent transformation into spin-singlet pairs and back.

Atom Interferometry with an Optical Lattice

Mikkel Andersen[1], Tycho Sleator[2]

[1] *Jack Dodd Center for Quantum Technology, Department of Physics, University of Otago, New Zealand*

[2] *Dept. of Physics, New York University, 4 Washington Place, New York, NY 10003, USA*

We have developed a new atom interferometer design, in which ^{85}Rb atoms are first cooled in an optical lattice in a MOT. The atoms are released at time $t = 0$, and then subjected at time $t = T$ to an off-resonant standing wave pulse. Around the time $t = (n + 1)T$ for integer $n \geq 1$, we detect the resulting atomic fringe pattern by applying a weak off-resonant optical traveling wave ("readout pulse") and observing the backscattered light from the atomic fringes. Figure 1 shows the resulting signals for $t \approx 2T$ (i.e., for $n = 1$).

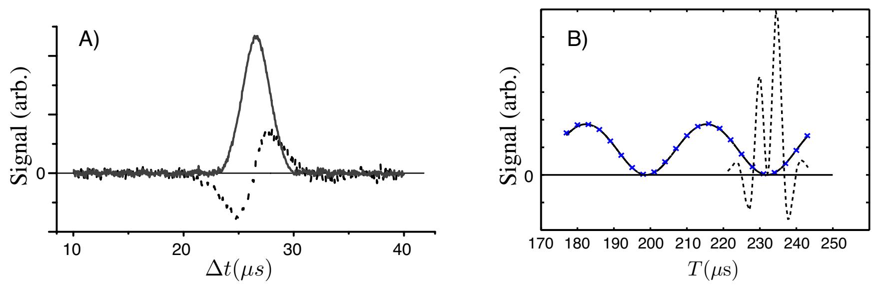

Figure 1: *A) Backscattered signal (solid line) as a function of time Δt from turn-on of readout pulse. Dashed curve shows the signal from previous interferometer configurations.*[1] *B) Peak signal [from A)] as a function of pulse delay T. $\times$'s show data for a short duration pulse ($\tau = 200$ ns), and solid curve is a fit to the data. Dashed curve shows data for a longer ($\tau = 1200$ ns) pulse.*

Theory and expriment tell us that the peak signal as a function of T is periodic in the recoil period $2\pi/\omega_r$, where $\omega_r \equiv 2\hbar k^2/m_{\mathrm{Rb}}$ is the recoil frequency and k is the wave-vector of the light[See Fig. 1B)]. For long pulses, the signal oscillates rapidly as a function of T, in principle allowing a more precise measurement of the recoil frequency. Although the theory only applies to short pulses (satisfying the Raman-Nath condition), we have carried out simulations of our experiment for longer pulses that show good agreement with the data.

We have also measured the maximum signal (as a function of T) for various pulse durations τ. We found that this maximum signal as a function of τ has an oscillatory component with a period of about 6.5 μs. These oscillations were also seen in simulations and the period was found to be close to that of a classical particle oscillating in the approximately harmonic potential near the minima of the potential created by the pulse. Our results may allow us to elucidate the effects of photon scattering on the interferometer visibility.

By collecting data for $n = 1$, 2, and 3, we can deduce the degree of localization of the atoms in the optical lattice just before they are released, and by also measuring the velocity spread, determine whether they are in thermal equilibrium in the lattice.

[1] See, e.g., Cahn *et. al* Phys. Rev. Lett. 79, 784 (1997).

Simulating Relativistic Physics with Ultracold Atoms

J. Y. Vaishnav, Charles W. Clark

Joint Quantum Institute, National Insitute of Standards and Technology, Gaithersburg MD 20899

A driving force behind the interest in ultracold atoms is their use as "quantum simulators" of other physical systems, including systems which are experimentally inaccessible in their original manifestations. In this poster, we propose an optical lattice setup under which ultracold atoms would feel effective Diraclike Hamiltonians. Such relativistic Hamiltonians underlie a variety of physical phenomena, ranging from *Zitterbewegung* to spintronics. Creating Diraclike Hamiltonians with cold atoms thus suggests a number of interesting experiments[1], which we outline in this poster.

[1] J. Y. Vaishnav and Charles W. Clark, *Physical Review Letters* **100**, 153002 (2008).

Multiplexed quantum repeater

A. G. Radnaev, S.-Y. Lan, O. A. Collins, D. N. Matsukevich, T. A. B. Kennedy, A. Kuzmich

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430

Quantum communication utilizes quantum entanglement to securely distribute information. The quantum repeater architecture holds promise for long distance quantum communication, however, scalability remains challenging. We have proposed to multiplex memory elements in order to drastically increase entanglement connection rates. We present an experiment demonstrating such multiplexing in cold rubidium.

Single Photon Nonlinearity in Cold Polar Molecular Arrays

T. Bragdon[1], R. M. Rajapakse[1], A. M. Rey[2], T. Calarco[2], S. F. Yelin[1,2]

[1]*Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[2]*Institue for Theoretical Atomic Molecular Physics, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*

We model single photon nonlinearities in arrays of cold polar molecules via long range dipole-dipole interactions. Decoherences are accounted for by the non-symmetric interaction and symmetric photon-molecule states as well as phonon dispersion. These effects are mitigated in many-body protected manifolds selected with tunable external fields. We discuss the feasibility of this system in optical quantum computation processing as an element of a controlled phase gate.

Progress Towards Spin - Photon Entanglement Using NV Centers in Diamond

E. Togan[1], Y. Chu[1], A. Trifonov[1], L. Jiang[1], M. V. G. Dutt[1,2], L. Childress[1,3], A. S. Zibrov[1], P. R. Hemmer[4], M. D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, MA, USA*
[2]*Department of Physics, University of Pittsburgh, Pittsburgh, PA, USA*
[3]*Department of Physics, Bates College, Lewiston, ME, USA*
[4]*Department of Electrical Engineering, College Station, TX, USA*

Recent work has demonstrated that individual Nitrogen Vacancy (NV) centers in diamond are promising candidates for quantum register systems. A register, made up of the electronic spin of the NV center and one[1] or few[2] nuclear qubits, may be used to store and manipulate quantum information. The challenge remains to entangle different registers to demonstrate scalability and to carry out more sophisticated functions, e.g. quantum repeaters, and quantum computers. In this work we show progress towards entangling one NV's spin to the photon emitted by the same center as a first step to using photon interference to generate entanglement between different NVs.

Spin-photon entanglement requires good control of the optical transitions of the NV as well as long coherence of the photons in emission. By using resonance fluorescence spectroscopy we identify and study various transitions, to determine their associated selection rules. The properties of these transitions are dependent on the local electric environment and strain, hence differ from NV to NV. Our observations of selection rules for various NVs are in agreement with recent theoretical predictions[3]. We then show that one can resonantly drive controlled optical Rabi nutations by selecting out a particular transition and use this method to obtain information on the coherence of the optical transition. We also show, while exciting an NV off resonantly, one can select out a particular set of transitions in emission and study their optical coherence on an unbalanced interferometer and a cavity.

Finally we propose a method for entanglement generation based on the demonstrated properties of the NV.

[1]M. V. Gurudev Dutt, et al., Science **316**, 1312 (2007).
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Few-qubit quantum registers encoded in alkaline-earth atoms trapped in an optical lattice

A. V. Gorshkov[1], A. M. Rey[2], A. J. Daley[3,4], G. Pupillo[3,4], P. Zoller[3,4], M. D. Lukin[1,2]

[1]*Physics Department, Harvard University, Cambridge, MA 02138, USA*
[2]*Institute for Theoretical Atomic, Molecular and Optical Physics, Cambridge, MA 02138, USA*
[3]*Institute for Quantum Optics and Quantum Information, 6020 Innsbruck, Austria*
[4]*Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria*

We propose methods to implement, manipulate, and couple few-qubit quantum registers encoded in alkaline-earth atoms trapped in an optical lattice. The methods rely on long-lived optical qubits and on the possibility of decoupling them from the nuclear spin degree of freedom. Applications in quantum information science and in many-body physics are discussed.

Quantum Repeater based on Atomic Ensembles

R. Zhao, Y. O. Dudin, S. D. Jenkins, C. J. Campbell, D. N. Matsukevich, T. A. B. Kennedy, A. Kuzmich

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430

Quantum mechanics provides a mechanism for absolutely secure communication between remote parties. For distances greater than 100 kilometers direct quantum communication via optical fiber is not viable, due to fiber losses, and intermediate storage of the quantum information along the transmission channel is necessary. This lead to the concept of the quantum repeater, proposed in 1998 by Briegel, Duer, Cirac, and Zoller. In 2001, Duan, Lukin, Cirac, and Zoller have proposed to use atomic ensembles as the basic memory elements for the quantum repeater. We will outline our program on the use of atomic ensembles as an interface for quantum information transfer and the prospects for long distance quantum networks.

Optimized planar Penning traps for quantum information processing

J. D. Goldman, G. Gabrielse

Department of Physics, Harvard University, Cambridge, MA 02138, USA

The spins of electrons in an array of planar Penning traps[1] have recently been proposed[2] as qubits for scalable quantum information processing. Such a system, which can be fabricated with existing technology, promises extremely long coherence times since the spin motion is extremely weakly damped ($\gamma_s^{-1} \sim 10^{11}$ s), the electrons are trapped in a cryogenic vacuum environment, and no quantum information is stored in motional degrees of freedom. Via QND coupling to the axial oscillation[3], the spin readout would be performed electronically and with effectively unit fidelity, a technique developed for high-precision measurements of the electron magnetic moment.[4]

Planar Penning traps have only just begun to be studied[5]. Before performing quantum logic operations, it is necessary first to develop for planar traps many of the techniques that have become well-established for cylindrical Penning traps, such as trapping, detecting, and manipulating the spin of a single electron.

As in any Penning trap, it is necessary to minimize the anharmonicity of the axial oscillator[6] so that thermal fluctuations of the axial amplitude do not broaden the axial resonance, which would obscure the signal from a single trapped electron and prevent detection of the small frequency shifts that differentiate its spin states. In a planar trap, anharmonicity compensation is further complicated by the lack of reflection symmetry about the center of the trapping potential.

We seek optimization of planar Penning trap design to establish locally harmonic behavior at a large amplitude, to minimize broadening due to thermal fluctuations of the axial energy, and to minimize sensitivity to the bias voltages applied to compensation electrodes.

[1] S. Stahl et al., *Eur. Phys. J. D* **32**, 139 (2005)

[2] G. Ciaramicoli, F. Galve, I. Marzoli, and P. Tombesi, *Phys. Rev. A* **72**, 042323 (2005). Other papers have also discussed using cylindrical Penning traps for quantum information processing.

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[4] D. Hanneke, S. Fogwell, and G. Gabrielse, *Phys. Rev. Lett.* (in press), `arXiv:0801.1134v1 [physics.atom-ph]`

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[6] Analogous to the work done with cylindrical traps in G. Gabrielse and F.C. MacKintosh, *Int J. Mass Spec.* **57**, 1 (1984) and G. Gabrielse, L. Haarsma, and S.L. Rolston, *Int. J. Mass Spec.* **88**, 319 (1989)

Anyonic interferometry and protected memories in atomic spin lattices

L. Jiang[1], G. K. Brennen[2], A. V. Gorshkov[1], K. Hammerer[2], M. Hafezi[1], E. A. Demler[1], M. D. Lukin[1], P. Zoller[2]

[1]*Physics Department, Harvard University, Cambridge, MA 02138, USA*
[2]*Institute for Theoretical Physics, University of Innsbruck, and Institute for Quantum Optics and Quantum Information of the Austrian Academy of Science, 6020 Innsbruck, Austria*

Systems with topological order can exhibit remarkable phenomena such as quasi-particles with anyonic statistics and might be used for naturally error-free quantum computation. Here we describe how to unambiguously detect and characterize such states in recently proposed spin lattice realizations using ultra-cold atoms or molecules trapped in an optical lattice. We propose an experimentally feasible technique to access non-local degrees of freedom by performing global operations on trapped spins mediated by an optical cavity mode. We show how to reliably read and write topologically protected quantum memory using an atomic or photonic qubit. Furthermore, our technique can be used to probe statistics and dynamics of anyonic excitations.

Mapping photonic entanglement into and out of a quantum memory

K. S. Choi, H. Deng, J. Laurat[,†], S. B. Papp, H. J. Kimble

Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA

In the field of quantum information science, of significant importance has been the development of scalable quantum networks, composed of quantum nodes for storing and processing information and photonic channels which link the remote nodes for entanglement distribution. Atomic ensembles can play the role of such nodes, where the collective interaction of single excitations and photons provide efficient means for the coherent transfer of quantum states between matter and light[1]. In this contribution, we report two advances toward this goal: entanglement distribution by asynchronous preparation of parallel pairs of atomic ensembles[2], and the reversible mapping of photonic entanglement into and out of atomic memories[3].

By following the seminal proposal by Duan *et al.*[1], two pairs of remote ensembles (∼3 m) at two nodes are each prepared in entangled states, in a heralded and asynchronous fashion by way of conditional control of the quantum memories[2]. After a signal heralding that the two pairs are entangled, the states of the ensembles are coherently converted to propagating fields locally at the two nodes such that they effectively contain two photons, one at each node, whose polarizations are entangled. The entanglement between the two nodes is verified by the measured violation of the CHSH inequality. The effective polarization entangled state is compatible with long-distance quantum communication protocols[1].

Beyond such probabilistic approaches[1], we also demonstrate a protocol where entanglement between two atomic ensembles is created by reversible mapping of an entangled state of light[3]. First, a single photon is split into two modes to generate photonic entanglement. This entangled field state is then coherently mapped to an entangled matter state in two atomic ensembles by way of dynamic Electromagnetically Induced Transparency (EIT)[4]. On demand, the stored entanglement is converted back into entangled photonic modes. The degrees of entanglement for input and output states are explicitly quantified with the transfer efficiency of entanglement approaching 20%. Our approach is inherently deterministic, suffering principally from the finite EIT efficiencies. Moreover, by separating the processes for the generation and storage of entanglement, contamination of atomic entanglement due to multiple excitations can be arbitrarily suppressed with advances in on-demand single photon sources. Our experiment thereby enables an alternative avenue to assist the distribution and storage of entanglement over quantum networks[1].

∗ This research is supported by IARPA and NSF.

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† *Present address : Laboratoire Kastler Brossel, Université Paris 6, Ecole Normale Superieure et CNRS, UPMC Case 74, 4 place Jussieu, 75252 Paris Cedex 05, France*

Quantum phase gates with polar molecules in an optical lattice

Elena Kuznetsova[1,2], R. Côté[1], Kate Kirby[2], S. F. Yelin[1,2]

[1]*Department of Physics, Uiversity of Connecticut, Storrs, CT 06269, USA*
[2]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*

Polar molecules have attracted significant interest as a viable platform for quantum computing. They combine the advantages of neutral atoms and trapped ions, such as long coherence times, rich level structure, strong optical and microwave transitions, and easy control by DC and AC electrc fields. This combination makes them compatible with various architectures, e.g. optical lattices and solid-state systems. Molecules with large permanent dipole moments can display strong dipole-dipole interactions, allowing for the construction of fast conditional two-qubit gates necessary to realize universal gates.

We analyze a recently proposed physical implementation of a quantum computer based on polar molecules with ”switchable” dipoles , i.e. dipole moments that can be switched ”on” and ”off” (Phys. Rev. A **74**, 050301(R), 2006). ”Switching” is realized by transferring a molecule by e.g. optical excitation between molecular states with significantly different dipole moments. We present a set of general requirements for a molecular system, which would provide an optimal combination of quantum gate times, coherence times, number of operations, high gate accuracy and experimental feasibility. We proceed with an analysis of a two-qubit phase gate realization based on switchable dipole-dipole interactions between polar molecules in an optical lattice architecture. We consider two of the schemes proposed in our previous work, a ”direct” and an ”inverted” scheme. We study the robustness of such a phase gate and analyze the experimental feasibility of the approach, using the CO and LiCs molecules as specific examples. We suggest suitable electronic states and transitions, and investigate requirements for the laser pulses driving them. Finally, we analyse possible sources of decoherence and list practical difficulties of the scheme.

Simultaneous measurements in quantum optics

M. Busshardt, M. Freyberger

Institute of Quantum Physics, Ulm University, Germany

Various possibilities for simultaneous measurements of conjugate variables in the optical domain are investigated. Here, for example, the quadratures of the electromagnetic field do not commute and therefore cannot be precisely measured simultaneously. Possible setups, necessary for measuring such non-commuting observables simultaneously by allowing the system to interact with certain classes of ruler systems, are reviewed and discussed. The question arises, which states of the ruler systems are optimal to gain specific information about the investigated system. This leads to generalized versions of the Heisenberg uncertainty relation.

High-Fidelity Readout of Trapped-Ion Qubits

M. J. Curtis, D. T. C. Allcock, A. H. Myerson, D. J. Szwer, S. C. Webster, G. Imreh, J. A. Sherman, D. N. Stacey, A. M. Steane, D. M. Lucas

Department of Physics, University of Oxford, United Kingdom

We present techniques relevant to trapped-ion qubits, and report experimental results utilizing these techniques in $^{40}Ca^+$ and $^{43}Ca^+$. Using a time-resolved photon counting technique we demonstrate single-shot qubit readout with a fidelity sufficient for fault-tolerant quantum computation[1]. For an optical qubit stored in $^{40}Ca^+$ we achieve 99.991(1)% average readout fidelity in 10^6 trials, using time-resolved photon counting. An adaptive measurement technique allows 99.99% fidelity to be reached in 145 μs average detection time. For $^{43}Ca^+$, we propose and implement an optical pumping scheme to transfer a long-lived hyperfine qubit[2] to the optical qubit, capable of a theoretical fidelity of 99.95% in 10 μs. We achieve 99.87(4)% transfer fidelity and 99.77(3)% net readout fidelity.
We will report our progress in performing an entangling gate between a $^{40}Ca^+$ qubit and a $^{43}Ca^+$ qubit held in a single r.f. ion trap.

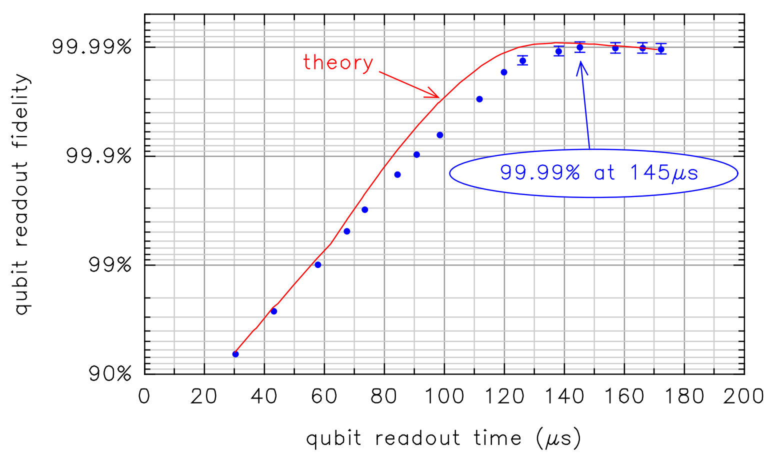

Figure 1: *Average readout fidelity against average readout time for the $^{40}Ca^+$ optical qubit, using adaptive time-resolved photon detection.*

We also generalize the optical Bloch equations so that they can be applied when transitions between pairs of states are driven by lasers with strong sidebands[3]. We show the theory reproduces well the observed response of a cold $^{40}Ca^+$ ion when subject to a single laser frequency driving the $4S_{1/2}$–$4P_{1/2}$ transition and a laser with two strong sidebands driving $3D_{3/2}$– $4P_{1/2}$.

[1] A. H. Myerson *et al. Phys. Rev. Lett* **100** 200502 (2008)
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Two-boson correlations in various quantum traps

A. Okopińska, P. Kościk

Institute of Physics, University of Humanities and Sciences
Świętokrzyska 15, 25-406 Kielce, Poland

We consider a system of two bosons that is able to model various physical situations by the appropriate choice of both the trapping potential and the interaction between the particles. First, we discuss the contact potential that is usually used to describe inter-particle interactions at ultra-low temperatures. The energy spectra for convex and non-convex confinement potentials are determined and various correlations characteristics are discussed. Entanglement properties are studied particularly carefully. Secondly, we perform an analogous study in the case of Coulomb and other long-range interactions between particles. In all the cases studied, a special attention is paid to the demonstration of the fermionization effects for strongly interacting particles.

Coherent control of electron-nuclear spin qubit registers

P. Cappellaro[1,2], L. Jiang[2], M. D. Lukin[1,2]

[1]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[2]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*

Motivated by recent experiments with single nitrogen-vacancy centers in diamond[123], we consider a few-qubit quantum system composed of a single electron and proximal nuclear spins and we describe a strategy for its efficient control.

Registers comprising a few qubits have gained attention as a possible paradigm for scalable quantum computers. The control of a small number of qubits has been demonstrated in many physical implementations while various proposals for integrating these small units into a larger system have been explored both theoretically [4] and experimentally [5]. These schemes most generally require a *communication* qubit and a few *ancillary* qubits per register, embedded in a hybrid architecture combining optical and solid-state systems. The *communication* qubits couple efficiently to external degrees of freedom (for initialization, measurement and entanglement distribution to other registers), leading to an easy control but at the same time to faster dephasing. The *ancillary* qubits on the other hand are more isolated and they can act as memory or as ancillas in error correction protocols.

Advances in coherent control of single electrons in solid-state systems have permitted to probe their environment[1,2] and to perform entangling operations[3]. The main cause of decoherence is often the nuclear spins [6]. Here we propose not only to reduce the noise by acting on the electronic spin, but also to coherently control part of the environment and use these additional degrees of freedom as qubits. Due to the large hyperfine coupling, the nuclear spins can be addressed individually: The electronic spin thus offers an access to these qubits that are otherwise well isolated and have therefore long coherence times.

The challenges to overcome are to resolve individual energy levels for qubit addressability and control, while at the same time avoiding fast electron dephasing due to the nuclear environment. We describe the system model and present a scheme for achieving these two goals. We analyze feasible performances and practical limitations of this approach in a realistic setting. This hybrid approach combines ideas from quantum optics, mesoscopic physics and NMR to yield a robust, potentially scalable quantum information system.

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Robust Generation of Superposition States

R. Yamazaki[1], K. Kanda[2], F. Inoue[2], K. Toyoda[1,2], S. Urabe[1,2]

[1] *JST-CREST, Saitama, Japan*
[2] *Graduate School of Engineering Science, Osaka University, Osaka, Japan*

Ion-trap based quantum information processing is considered to be one of the promising candidates for the large scale quantum computer. Fundamental building blocks, including the qubit initialization, single and two-qubit operation, and state read out have already been demonstrated in the ion-trap system. Much of the recent effort is concentrated in the development of high-fidelity and robust operations.
We report here the experimental results of generation of superposition state in a two level system, $4s\,S_{1/2}$ and $3d\,D_{5/2}$ states, of a single calcium ion. The generation method is based on population transfer via rapid adiabatic passage (RAP), proposed by Vitanov and Shore[1]. The quadrupole transition between the two states is excited with a laser pulse with controlled amplitude shape and linear frequency chirp to steer the initially prepared state to super-position states. The coherence of the generated superposition states is evaluated with Ramsey method. Following the superposition state generation, a π/2-pulse with different phase, ϕ, is introduced to rotate the generated state. Projective measurements of the rotated state showed sinusoidal modulation and fringe visibility of up to 0.93 is obtained. The state generation shows strong robustness with respect to the variation in the Rabi-frequency of the probing laser.
Application of the method in collective addressing of array of ions and in manipulation of "optically-thick" material, including a BEC system, is discussed. The current limitations, including the technical limitations, and state generation speed are also discussed.

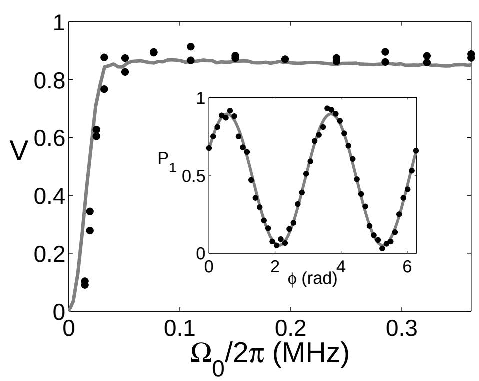

Figure 1: *Coherence measurement of the generated superposition states. Visibility (V) obtained with Ramsey-method for different probe laser Rabi-frequency is shown along with the line showing the simulation result. The inset shows a typical Ramsey fringe observed in the experiment.*

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Studying the Rydberg blockade with individually trapped single atoms in optical tweezers

A. Gaëtan[1], Y. Miroshnychenko[1], T. Wilk[1], C. Evellin[1], G. Messin[1], A. Browaeys[1], P. Grangier[1], M. Viteau[2], A. Chotia[2], D. Comparat[2], P. Pillet[2]

[1] *Laboratoire Charles Fabry de l'Institut d'Optique, Palaiseau, France*
[2] *Laboratoire Aimé Cotton, Orsay, France*

In our experiment we want to investigate the Rydberg blockade with two single ^{87}Rb atoms each trapped in an optical tweezer. This effect, recently observed for two single atoms[1], will enable the realization of fast quantum gates[2]. With our experimental apparatus, which allows us to trap single atoms in optical tweezers, to individually manipulate their internal states and to move them around without losing their coherence[3], we have a very versatile tool at hand to explore the blockade mechanism for applications in quantum information processing.
The key element of our setup is a microscope objective with a high numerical aperture. It allows us to focus the dipole trap beam to a waist of less than 1μm, which guarantees the trapping of only one atom per trap[4]. Two separated traps with a variable distance are created by sending two dipole trap beams with an adjustable tilt through the objective. Each trap is separately imaged through the microscope objective onto an avalanche photodiode. When shining in molasses beams, the level of observed fluorescence light tells us about the presence of an atom in each of the traps. Moreover, the tight focusing of the trap beams allows us to individually address the atoms and to drive Raman transitions between the hyperfine levels of the $5S_{1/2}$ ground state, which form our qubit states.
To investigate the Rydberg blockade regime we study the two-photon resonance for a single atom from the $5S_{1/2}$ ground level to the $58D_{3/2}$ Rydberg state. After optically pumping the atom in the F=2, m_F=2 state of the $5S_{1/2}$ ground level, we drive the two photon transition using one π-polarized laser close to the D1-line of Rb (795 nm) which is detuned by 1.2 GHz with respect to the $5P_{1/2}$, F=2 level and a second σ^+-ploarized laser at a wavelength of 475 nm. A magnetic field of 3.5 G defines the quantization axis. Once in the Rydberg state, the atom is lost from the trap and we observe no fluorescence light when shining in the molasses beams. For two atoms located at a distance of about 3μm we expect a shift of the energy level for the Rydberg-Rydberg system of hundreds of MHz with respect to non interacting Rydberg atoms. The status of the experiment will be reported.

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Controlled Creation of Spatial Superposition States for Single Atoms

Th. Busch[1], K. Deasy[2,3], S. Nic Chormaic[1,2,3]

[1]*Physics Department, University College Cork, Cork, Ireland*
[2]*Dept. of Applied Physics and Instrumentation, Cork Institute of Technology, Cork, Ireland*
[3]*Photonics Centre, Tyndall National Institute, Cork, Ireland*

Controlling the quantized centre-of-mass state of a single atom in an array of microscopic potentials has become a focus of experimental and theoretical research in recent years. Optical lattices and microscopic optical or magnetic traps allow one to trap single atoms in individual, well-separated sites between which atoms can coherently move via tunneling. Recently it has been suggested that adiabatic techniques could be used to control tunneling processes with high fidelity analogously to the optical STIRAP [1].
Here, we show how additional degrees of freedom present in an atomic setting can be used to develop new and useful techniques, based on STIRAP, for preparing and processing quantum states. We will show how to create atomic spatial superposition states with a fully controllable phase relation and demonstrate how these technique can be used to construct an atomic interferometer. We will also show how these processes can find applications in quantum computing schemes.

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Entangling single trapped atoms and ions

H. Dörk-Bendig[1], Z. Idziaszek[2,3], P. S. Julienne[4], A. Simoni[5], P. Zoller[6], T. Calarco[1]

[1]*Institute for Quantum Information Processing, University of Ulm, Germany*
[2]*Institute of Theoretical Physics, University of Warsaw, Poland*
[3]*Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland*
[4]*National Institute of Standards and Technology, Gaithersburg, Maryland, USA*
[5]*Laboratoire de Physique des Atomes, Lasers, Molécules et Surfaces, Rennes, France*
[6]*Institute for Quantum Optics and Quantum Information, Innsbruck, Austria*

When a neutral atom and an ion are brought together, the ion charge induces in the atom an electric dipole moment, which attracts it with an internal-state-independent r^{-4} dependence at large distances. The short-range part of the interaction potential, conversely, presents an intricate dependence on the diatomic molecular state, exhibiting many features known from atomic collision physics, for instance Feshbach resonances[1]. In confined geometries, the bigger interaction strength of the induced-dipole potential, compared to neutral collisions, gives rise to novel phenomena like trap-induced resonances.
An increasing number of experimental groups worldwide are showing interest and/or starting experiments with combined charged-neutral systems in various configurations. This opens up a perspective for manipulating ion-atom systems down to single-particle control.
In this work, we focus on a single trapped ultracold neutral atom and an ion, with the aim of generating and controlling entanglement between them. We analyze the basic interaction mechanisms, solve the eigenvalue problem under variable experimental configurations[2] and discuss how to perform an entangling process exploiting different mechanisms, from phonon exchange between relatively distant traps to trap-induced and Feshbach resonances between quasi-overlapping particles.

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Breaking the dipole blockade: Nearly-resonant dipole interactions in few-atom systems

T. Pohl[1], P. R. Berman[2]

[1]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge MA 02138, USA*
[2]*Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA*

The dipole blockade, in which Rydberg atom - Rydberg atom interactions inhibit all but a single collective Rydberg excitation, has been proposed as a mechanism to store and manipulate quantum information in mesoscopic ensembles.

In the simplest case of two interacting atoms, the dipole blockade arises from strong dipole coupling to adjacent Rydberg states which, at sufficiently small interatomic separations, shifts the doubly-excited state strongly out of resonance. As a result, when the atoms are excited by a pulsed laser field, they are driven between the two-atom ground state and two-atom singly-excited state with a Rabi frequency that is collectively enhanced by a factor of $\sqrt{2}$.

It would seem reasonable that the presence of further close-by atoms would add to the efficiency of the dipole blockade, allowing only a single Rydberg excitation that is coherently shared among all N atoms, the excitation characterized by a collectively enhanced Rabi frequency of $\sqrt{N}\Omega$. Here we show that this is not necessarily the case $-$ *the presence of a third atom can break the dipole blockade*.

We obtain the molecular states of the three atoms, and identify an *interaction-free, dark state* in which each of the atoms is in a Rydberg state. Using an adiabatic elimination scheme, we derive simple expressions for the three-atom excitation dynamics. We find that the combined interaction of three atoms, each of which pairwise would produce a blockade, breaks the dipole blockade. The dark state plays a critical role in this process.

Several examples will be given that reveal an interesting dependence of the excitation probability on the combined role of atom-field detuning, laser field strength, and dipole-dipole coupling. Moreover, we present numerical simulations that demonstrate the importance of many-atom effects on the excitation dynamics in small ensembles. Our analytical results, together with the many-atom simulations, show that a careful choice of laser parameters must be made in order to optimize the blockade efficiency.

Towards controlled interactions with individual atoms: Detecting nearest neighbors in an optical lattice and controlled atom-field coupling in an optical cavity

A. Widera, W. Alt, J.-M. Choi, L. Förster, T. Kampschulte, M. Karski, M. Khudaverdyan, L. Kong, S. Reick, K. Schörner, A. Thobe, D. Meschede

Institut für Angewandte Physik, Universität Bonn, 53115 Bonn, Germany

Creating and investigating arbitrary quantum states at will is an intriguing perspective of quantum engineering. This, however, requires ultimate control in preparation, manipulation and detection of quantum systems on a single particle level. Here, we report on recent advances in the detection of individual neutral atoms in adjacent micropotentials of an optical lattice. Further, we present controlled manipulation of single atoms either in spin dependent potentials or by coupling them to a high finesse optical cavity. This opens new routes to tightly control and detect atom-atom interactions in an optical lattice.

In our experiments, we load up to ten laser cooled Cesium atoms from a magneto-optical trap into a 1D optical standing wave. Using fluorescence imaging and real time numerical processing of these images we are able to deduce atomic positions far beyond the standard diffraction limit, even down to nearest-neighbor distances in the optical lattice (~ 435 nm). For manipulation of atoms, we make use of a "magic" lattice wavelength between the D_1 and D_2 lines of Cesium. Together with active polarization control of the laser light forming the optical lattice, this establishes a spin dependent transport[1] for single Cesium atoms which we have performed over up to ten lattice sites.

Finally, in a different approach, we are able to induce a controlled strong interaction between atoms and single photons in a high-finesse optical resonator. This coupling is continuously maintained on a minute time scale and reveals an intriguing intra-cavity dynamics of a single atoms coupled to the cavity field. Moreover, we have established dispersive spin-selective detection of an atom in the cavity. Combining this detection method with our long coupling times paves the way to investigating atom-field coupling in a practically heating free situation at high repetition rates.

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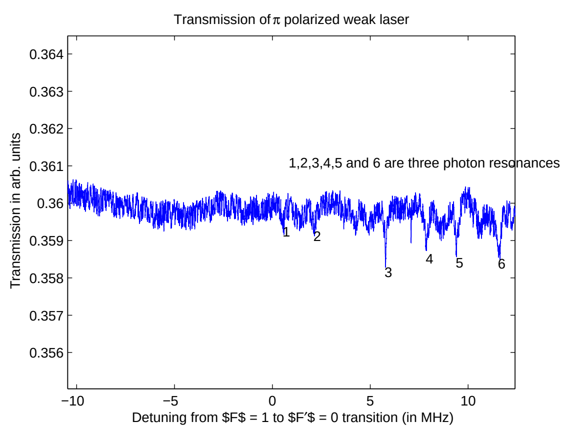
Threshold three photon resonance in Zeeman transitions

A. Hazra[1], A. Narayanan[1], S. N. Sandhya[2]

[1]*Raman Research Institute, Bangalore - 560 080, INDIA*
[2]*Department of Physics, IIT Kanpur - 208016, INDIA*

Non-linear light matter interactions in coherent matter shows very different behaviour from such effects in incoherent matter. Coherence between electronic or hyperfine energy levels of gaseous atomic samples can be established through the phenomenon of Electromagnetically Induced Transparency (EIT). In such systems, EIT based Kerr effect, arising from the refractive part of third-order susceptibility in a four-level system, is studied as an absorption in a probe beam modified by signal and coupling beams [1]. We report that such a three photon absorption, shows a sharp threshold around F′ = 0, in Zeeman degenerate transitions of F = 1 and F′ = 0,around the D2 line in ^{87}Rb. The threshold can be attributed to a competition between transparency induced depletion of population in the $m_F = 0$, F = 0 sub-level and off-resonant optical pumping of coherences and population through F' = 1 to this sub-level. The sharpness of this threshold, depends on the nature of coherent state formed. A maximally coherent ground state (a CPT state) creates a sharper threshold. This threshold behaviour may be made use of in making a frequency switch for quantum logic gates.
Three beams L1, L2 and L3, derived from a single laser irradiate a sample of vapour cell Rubidium atoms. L2 and L1 beams show transparency (EIT) of width 1 MHZ at $\delta_{L2} = \delta_{L1}$. Shown in the Figure are absorption features (1-6) seen in L3 beam, of width 200 KHz, at positions of transparency resonances. Scanning the laser frequency using an AOM at any fixed laser position helps in seeing both the EIT and absorption signals. We see in the figure that there is a complete lack of this absorption feature a few MHz red of $F' = 0$,followed by a good contrast absorption at F' = 0 and above. Absorption resonances continue all the way upto $F' = 1$.



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Few-photon photon nonlinear optics with cold atoms inside a hollow core fiber

M. Bajcsy[1], S. Hofferberth[1], V. Balic[1], T. Peyronel[2], A. S. Zibrov[1], V. Vuletić[2], M. D. Lukin[1]

[1]*Physics Department, Harvard University, 17 Oxford St., Cambridge, MA 02138, USA*
[2]*Physics Department, MIT, 36 Vassar St., Cambridge, MA 02139, USA*

Physical processes that can facilitate nonlinear interactions between weak light pulses have been explored for several decades. In addition to fundamental interest, these efforts are stimulated by potential applications ranging from development of few-photon switches and optical transistors to quantum information science. Confining cold atoms and photons to a diameter comparable to optical wavelength inside a hollow core photonic crystal fiber dramatically enhances the probability of interaction between a single photon and a single atom. As a result, an atomic ensemble consisting of a few hundred atoms will create a high optical depth medium that needs only a comparable number of photons to saturate and that can act a mediator for interactions between few-photon pulses. Here, we present an experimental system that uses this novel approach to achieve strong, coherent nonlinear interactions between few-photon pulses and atoms. We study the unique features of this system by demonstrating coherent control techniques such as Electromagnetically Induced Transparency (EIT) and nonlinear all-optical switching with few hundred photons per control/switch pulse.

Entanglement in the adiabatic limit of cavity QED with pairs of atoms

C. Lazarou, B. M. Garraway

Department of Physics and Astronomy, University of Sussex, Brighton, UK

We analyse the problem of a time dependent 2-atom Tavis-Cummings Hamiltonian in the adiabatic limit. Instead of the usual constant coupling between a single mode cavity and a pair of atoms, we utilise the spatial profile of the interaction by having time dependent coupling functions. In considering the adiabatic limit, we were able to demonstrate the presence of an energy crossing degeneracy which plays a key role in the dynamics[1]. Furthermore, we show that it is possible to achieve conditional entanglement between the cavity and the atoms or generate a maximally entangled state of the two atoms[1,2]. Using the fidelity for particular entangled states, and the concurrence for bipartite and tripartite systems, we derive the properties of entanglement between all three systems. We also study the effect that cavity losses or atomic spontaneous emission have on the system[2].

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Teleportation of resonance fluorescence: bandwidth and squeezing requirements

C. Noh, H. J. Carmichael

Department of Physics, University of Auckland, Auckland, New Zealand

The pioneering experimental work of Furusawa et al. on continuous variable quantum teleportation[1] can be looked upon within the framework of the teleportation of quantum fields: there is a continuous beam of light into and out of the teleporter. We take this point of view and ask under what conditions such teleportation may be deemed successful. In this work the scattered field of resonance fluorescence is adopted as the input, since it provides clear signatures (Mollow triplet, photon antibunching), which one can look for in the teleported output. Because the input field is broadband, filtering is essential and we find various constraints on the bandwidths for successful teleportation. The relevant bandwidths involved are those of the input field, correlated EPR fields, Alice's filtering of her photocurrents, and Bob's filtering of the output. We calculate the spectra and intensity correlation functions of the teleported field, and compare them with those of the input field to find the bandwidths and amount of squeezing required for successful teleportation. To calculate the spectra and intensity correlation functions we adopt the method suggested by Ralph[2]. In this method we treat Alice's quadrature measurement signals (photocurrents) formally as operators, which allows us to work with a linear mapping between the input and the output fields . We can then calculate the correlation functions of the output field in terms of those at all inputs (input field and correlated EPR fields). It is worthy of note that this scheme lies in one-to-one correspondence with a treatment of continuous variable teleportation within the framework of stochastic electrodynamics[3]; the former treats all noise processes as quantum operators (both quantized fields and classical currents), while the latter treats them all as classical processes
We first introduce the standard continuous variable teleportation scheme[4], extended to account for the bandwidths and filtering mentioned above. Then we describe the linear mapping between input and output fields and its relationship to stochastic electrodynamics. We derive the spectrum of the output field and show how each bandwidth affects the teleported spectrum. Finally, we derive the teleported intensity correlation function and show the effects of the various bandwidths and degree of squeezing on it. We find very stringent requirements on the relative bandwdiths and the degree squeezing in order to achieve high-fidelity teleportation, particularly of the photon correlations. Optical filtering of the output field by Bob is essential to remove excess noise arising from imperfect matching of Alice's measurement spectrum to the spectrum of squeezing.

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Dicke-Bose-Hubbard model

Soi-Chan Lei[1], Ray-Kuang Lee[1,2],

[1]*Physics Department, National Tsing-Hua University, Hsinchu 300, Taiwan*
[2]*Institute of Photonics Technologies, National Tsing-Hua University, Hsinchu 300, Taiwan*

We extend the idea of quantum phase transitions of light in atom-photon system with Dicke-Bose-Hubbard model for arbitrary number of two-level atoms. The formulations of eigenenergies, effective Rabi frequencies, and critical chemical potentials for two atoms are derived. With a self-consistent method, we obtain a complete phase diagram for two two-level atoms on resonance, which indicates the transition from Mott insulator to superfluidity and with a mean excitations diagram for confirmation. We illustrate the generality of the method by constructing the dressed-state basis for arbitrary number of two-level atoms. In addition, we show that the Mott insulator lobes in the phase diagrams will smash out with the increase of atom numbers. The results of this work provide a step for studying the effects with combinations of Dicke-like and Hubbard-like models to simulate strongly correlated electron systems using photons.[1]

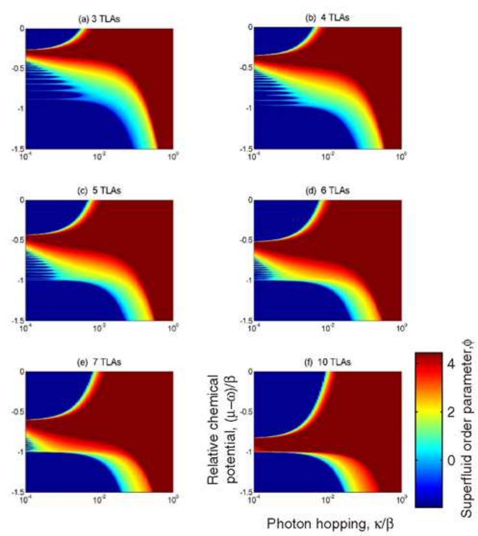

Figure 1: *The phase diagrams for arbitrary number of TLAs, (a)* $N = 3$*, (b)* $N = 4$*, (c)* $N = 5$*, (d)* $N = 6$*, (e)* $N = 7$*, and (f)* $N = 10$*. The notation SF refers to a superfluid phase with strong interaction of photon hopping while MI refers to a Mott insulator phase with equally number of photons in each cavity.*

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Coherent Control of One Atom Strongly Coupled to an Optical Cavity

D. Wilson, R. Miller, T. E. Northup, A. D. Boozer, H. J. Kimble

Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, CA 91125, USA

Quantum networks based on cavity QED will require robust tools for coherent manipulation of intracavity atoms.[1] In a recent experiment, we demonstrated localization to the ground state of motion for a single cesium atom strongly coupled to the field of a high finesse optical resonator.[2] Our advance was made possible by a Raman scheme tailored to the geometry of the cavity mode. A variation on this scheme provides coherent control over the hyperfine and Zeeman state of the trapped atom. Namely, we use our standing-wave dipole trap as one arm of the Raman pair. We demonstrate how this scheme can be used – in conjunction with efficient hyperfine state detection – to conditionally load one or two atoms into the cavity. We show how incoherent Raman transitions can then be used to prepare the atom(s) in an arbitrary Zeeman state with $\sim$ 60% efficiency.[3] By driving coherent Raman transitions, we are able to transfer population between the hyperfine ground states of the trapped atom. We are also able to map a superposition of the atom's Zeeman states onto its hyperfine states, enabling us to retrieve information about the Zeeman coherence. We use Rabi oscillations, spin echo, and Ramsey interferometry to investigate decoherence mechanisms in our experiment. We also discuss the application of our Raman scheme to atom-photon and atom-atom entanglement protocols in cavity QED.

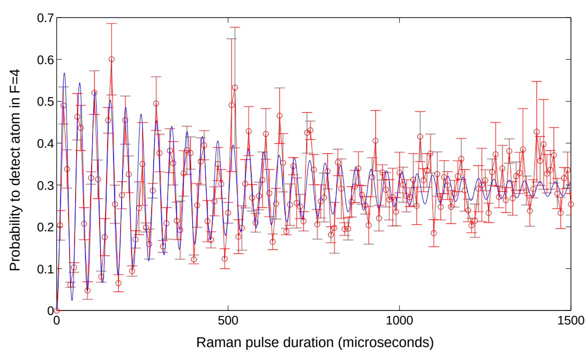

Figure 1: *Rabi oscillation between $|F{=}3,m{=}0\rangle$ and $|4,0\rangle$. For each measurement, atoms are prepared with $\sim$60% efficiency in $|3,0\rangle$, then driven with a raman pulse of varying duration, followed by state detection. A magnetic field along the cavity axis splits the Zeeman levels by $\sim$500kHz. Here the raman pulse is detuned 5kHz to the red of the $|3,0\rangle \leftrightarrow |4,0\rangle$ transition. Decoherence is related to the temperature of the trapped atom.*

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Generating single-photon nonlinearities and strongly correlated photonic states using nanoscale optical waveguides

D. E. Chang[1], A. S. Sørensen[2], V. Gritsev[1], G. Morigi[3], V. Vuletić[4], E. A. Demler[1], M. D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2]*Niels Bohr Institute, DK-2100 Copenhagen Ø, Denmark*
[3]*Grup d'Optica, Department de Fisica, Universitat Autonoma de Barcelona, 08193 Bellaterra, Spain*
[4]*Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

A number of methods to guide light that is transversely confined near or below the diffraction limit have been actively explored in recent years. The technologies that have attracted considerable interest include tapered optical fibers, hollow-core photonic crystal fibers, and conducting nanowires that support surface plasmon modes. The tight transverse confinement enables strong interactions between single guided photons and single optical emitters, which can be further manipulated by introducing quantum optical control techniques to these systems. As an example, we show how such techniques can be used to realize strong, controllable interactions between single photons mediated by a single resonant emitter. This nonlinearity can be applied to implement a single-photon transistor, where the presence or absence of a single photon in a “gate” field controls the propagation of a much larger optical “signal” field. Furthermore, we demonstrate that the large optical nonlinearities achievable in these systems can also give rise to strongly correlated states involving many photons. In particular, we describe a method to create a “crystal” of photons beginning from a non-interacting, classical optical pulse. Here, an effective repulsive interaction among the photons causes them to separate and “self-organize” into a crystal. Finally, we investigate the feasibility of creating nanoscale atomic traps using plasmonic systems to form an interface between atomic physics and quantum nano-optics.

Strongly correlated photon transport in nonlinear optical fiber

M. Hafezi, D. E. Chang, V. Gritsev, E. A. Demler, M. D. Lukin

Department of Physics, Harvard University, Cambridge, MA 02138

We present a theoretical investigation of quantum transport of photons through a one-dimensional waveguide whose propagation is described by the quantum non-linear Schrödinger equation. Such systems are now being implemented using a hollow-core fiber loaded with trapped alkali atoms. The tight transverse confinement of the photonic modes enables a large atom-field coupling strength and correspondingly large atom-mediated optical nonlinearities. These effects are observable at the level of few-photon behavior. In particular, we analyze the quantum correlation functions of a weak classical input field transmitted through a finite system. We observe that the transmitted light exhibits anti-bunching in the presence of *repulsive* interactions between photons, as shown in Fig. 1. This anti-bunching is the consequence of delocalization of photons inside the nonlinear medium and the reflection of bunched components (*i.e.*, two photons) of the input field when the system is tuned to the one-photon transmission resonance. The case of *attractive* nonlinearity shows both bunching and anti-bunching behavior, which arises from competition between the change in mode structure due to nonlinearities and the localization of photons inside the medium. The widely tunable nonlinearity in the system enables one to coherently control statistical properties of photon fields.

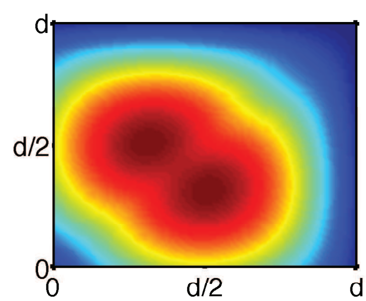

Figure 1: *Due to a positive nonlinearity, photons repel each other. This is manifested in delocalization of the two-photon wave function inside the nonlinear medium.*

Cavity QED with ion Coulomb crystals

P. Herskind, A. Dantan, J. Marler, M. Albert, M. B. Langkilde-Lauesen, M. Drewsen

QUANTOP, Department of Physics and Astronomy, University of Aarhus, Denmark

In addition to its fundamental interest for atom-light studies, Cavity Quantum Electrodynamics (CQED) represents an interesting avenue for engineering efficient light-matter quantum interfaces for quantum information processing. Experiments with neutral atoms have been very successful in strongly coupling single atoms to cavities of extremely small mode volume and very high finesse. These experiments are, however, challenged by the difficulty in confining and storing the atoms in the cavity for a long time [1].

Ions, on the other hand, have proved to be an excellent medium for quantum information processing and benefit from very long trapping times, a good localization and are robust against decoherence. Although significant progress has been made within the field and single ions have been coupled to high finesse cavities [2] [3], minimizing the mirror separation, without severely modifying the trapping potential has made it extremely difficult to reach the strong coupling regime with single ions. The small mode volume requirement can be relaxed for ensembles of atoms or ions though, due to the enhancement of the collective coupling strength of the ensemble and clouds of cold ions thus represent an interesting alternative system to a single atom or ion.

When a trapped cloud of ions is cooled below a certain critical temperature, the ions form a spatially ordered state, known as an ion Coulomb crystal. In addition to tight confinement and long storage times, ion Coulomb crystals also have a number of advantages over cold atomic samples. As the ions are confined in a crystal lattice, the decoherence rate due to collisions is very low and their low optical densities (10^8 cm^{-3}) make optical pumping and state preparation unproblematic. Finally, the inherent lattice structure in conjunction with the standing wave field of the optical resonator opens up for new possibilities to engineer the atom-photon interaction.

We will present recent experimental results on CQED with cold ion Coulomb crystals of calcium, obtained by using a novel linear radio frequency trap incorporating a moderately high finesse cavity ($\mathcal{F} \sim 3000$). Even though the 3-mm diameter dielectric cavity mirrors are placed between the trap electrodes and separated by only 12 mm, it is possible to produce *in situ* ion Coulomb crystals containing more than 10^5 calcium ions of various isotopes and with lengths of up to several millimetres along the cavity axis [4]. Single to a few thousands of ions can be stored in the cavity mode volume and efficiently prepared by optical pumping in a given magnetic substate of the metastable $4\mathrm{d}^2\mathrm{D}_{3/2}$ level of $^{40}\mathrm{Ca}^+$. The first results on the crystal-light coupling strength - evaluated by probing the ion-cavity system at the single photon level - as well as the possibilities for CQED experiments offered by this new system, will be discussed.

[1] P.R. Berman (Ed.) Cavity Quantum Electrodynamics, Academic Press inc., London (1994)

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Novel systems for single-photon generation using quantum memory

S. Hormoz[1], P. Walther[1], A. Nemiroski[1], M. Klein[1,2], D. Patterson[1], A. V. Gorshkov[1],
A. S. Zibrov[1], R. Walsworth[1,2], J. M. Doyle[1,3], M. D. Lukin[1,3]

[1]*Physics Department, Harvard University*
[2]*Harvard-Smithsonian Center for Astrophysics*
[3]*Harvard-MIT Center for Ultracold Atoms*

The effective generation of single photons on demand is one of the most important prerequisites for scalable quantum computation and quantum communication using linear optics and measurement-induced nonlinearities. Using atomic memories and the controlled interaction of photons and atoms could allow for the realization of such single-photon sources. One promising approach is based on writing and reading single excitations in atomic ensembles using Raman processes and electromagnetically induced transparency. We report on the development of two novel experimental systems for the realization of such single-photon sources, each combining long coherence times with high efficiencies and purity. The first approach makes use of 1mm-wide paraffin-coated Rubidium cells at room temperature whose volumes are in the order of the interaction region. The second approach makes use of buffer gas cooling to create an appropriate dense medium with excellent coherence properties. Experimental realization and comparison of these two approaches will be presented.

Interference in the light emitted by a single tunneling atom

J. Martin, D. Braun

Laboratoire de Physique Théorique, Université de Toulouse III, CNRS, 31062 Toulouse, France

We consider the tunneling of a two-level atom in a double well potential while the atom couples to the full continuum of electromagnetic modes in three dimensions (see Fig. 1). The study is within the Lamb-Dicke regime concerning transitions to higher vibrational states, but beyond the Lamb-Dicke regime concerning the tunneling splitting. The tunneling process may decohere, depending on the wavelength corresponding to the internal transition and on the spontaneous emission rate[1]. Interference fringes appear in the emitted light from a tunneling atom, or an atom in a stationary coherent superposition of its center-of-mass motion, if the wavelength is comparable to the well separation and if the external state of the atom is post-selected. If the atom couples to a single electromagnetic field mode of a cavity instead of the full continuum, the coupling between internal and external degrees of freedom of the atom induced by the cavity mode can dramatically change the tunneling behavior[2].

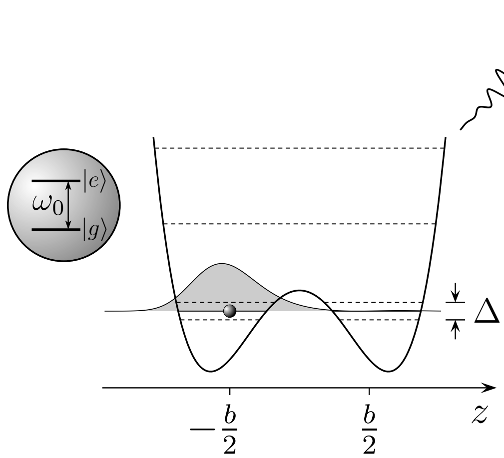

Figure 1: *Emission of a photon by a two-level atom tunneling in a double-well potential.*

[1] D. Braun, J. Martin, Phys. Rev. A **77**, 032102 (2008)
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Fast Excitation of a Coupled Atom-Cavity System

J. Bochmann, M. Mücke, B. Weber, H. P. Specht, D. L. Moehring, G. Rempe

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

Single atoms coupled to high finesse optical cavities provide unique systems to study light-matter interactions in the quantum regime. Naturally, these systems are well suited for atom-photon entanglement [1] and distributed quantum networks [2].

Here, we report on the fast excitation of a single atom coupled to an optical cavity using laser pulses that are much shorter than all other coherent and incoherent processes (atom-cavity coupling strength g, atomic polarization decay rate γ, and cavity field decay rate κ). It results in a near-instantaneous promotion of the atom to the excited state. Subsequently, the coupled atom-cavity system displays an oscillatory energy exchange between the atom and the cavity field. Thus, a photon is deposited in the cavity and is finally emitted into a well-defined spatial output mode. The shape of the single photon wavepacket is independent of the excitation pulse and only governed by the dynamics of the coupled atom-cavity system [3].

We show that the cavity frequency can be used as a parameter to control the photon's shape and frequency spectrum. Moreover, the excitation scheme allows us to generate single photons on an atomic cycling transition in a cavity QED environment. It can improve existing atom-photon entanglement experiments[1] by reducing unwanted multiple-photon events and can possibly extend them to multi-photon entanglement protocols. Moreover, a single photon in a superposition of two tunable frequencies as demonstrated here may be useful as a frequency qubit [4].

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[2] P. Zoller et al, Eur. Phys. J. D **36**, 203 (2005)
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Atomic qubit detection in the strong coupling regime

J. Volz[1], G. Dubois[1], R. Gehr[1], Y. Colombe[1,2], J. Reichel[1]

[1] *Laboratoire Kastler Brossel, ENS, 24 rue Lhomond, 75005 Paris, France*
[2] *NIST, 325 Broadway, Boulder, Colorado 80305, USA*

Microchip based atom traps are a promising approach towards quantum information and communication with neutral atoms. One crucial task for the realization of these protocols is a highly efficient state detection of atomic qubits.
In our experiment we realize the detection of single atoms using a cavity in the strong coupling regime. For this purpose we mount two fiber based cavities onto a micro-fabricated atom chip[1]. We detect single trapped atoms via measuring the transmission of the resonator. Therefore, we load a small ensemble of ^{87}Rb atoms (≈ 10) out of a Bose-Einstein condensate (BEC) into a single antinode of the intra-cavity standing wave dipole trap. The cavity is resonant with the F=2 to F'=3 transition of ^{87}Rb and the atoms are initially in the F=1 ground state. Using weak microwave pulses we transfer single atoms to the F=2 ground state resonant with the cavity. Each time an atom is transferred, we observe a drop in cavity transmission by orders of magnitude which allows to detect the presence of the atom within a few μs with a probability close to unity.

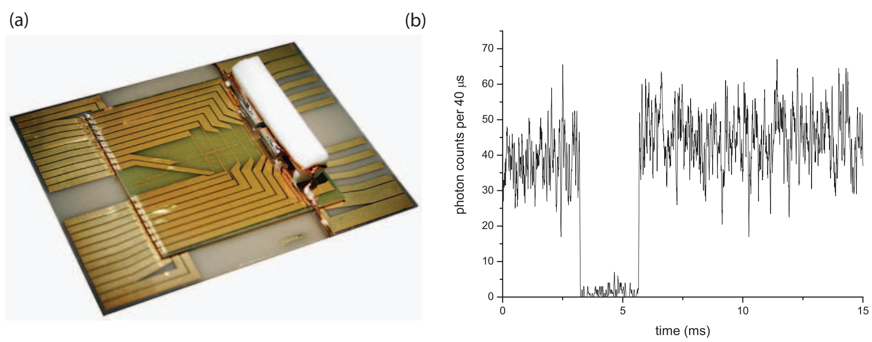

Figure 1: *(a) Setup of the chip and the cavity consisting of two high-reflection coated optical fibers. (b) Cavity transmission measured using an avalanche photo diode. Due to the presence of a resonant atom inside the cavity a large drop in transmission can be observed.*

[1] Y. Colombe, T. Steinmetz, G. Dubois, F. Linke, D. Hunger and J. Reichel, Strong atom-field coupling for Bose-Einstein condensates in an optical cavity on a chip. Nature 450, 272-276(2007)

Engineering the EIT optical response of a five level atom via two ground state RF transitions

J. O. Weatherall[1,2], C. P. Search[1]

[1]*Department of Physics and Engineering Physics, Stevens Institute of Technology, Hoboken, NJ 07030, USA*
[2]*Department of Logic and Philosophy of Science, University of California, Irvine, CA 92697, USA*

We consider the linear optical response of a collection of N five level atoms consisting of four different hyperfine ground states and a single optically excited state $|a\rangle$. Following the standard electromagnetically induced transparency (EIT) configuration, one of the ground states, $|c\rangle$, is coupled to the excited state via a strong resonant control beam while the transition between the excited state and a second ground state, $|b\rangle$, is probed by a second, weak laser. Each of these ground states is coupled to an additional ground state via an RF field (see Fig. 1).
As with standard EIT, we find that the strong control beam "dresses" the atom, effectively splitting the absorption profile for the probe beam into two peaks, with a transparency window at the bare transition frequency. However, inside this transparency window two new ultra-narrow absorption resonances arise due to the RF coupling to the additional ground states. The locations and line widths of these new features are fully controlled by the Rabi frequencies of the RF fields and moreover the line widths can be made several orders of magnitude smaller than the natural line width of $|a\rangle$, γ_a. We show how these new resonances and the ultra-narrow line widths can be readily interpreted in terms of the energy eigenstates of the atoms. Near the new features, the dispersion also varies dramatically with the RF field Rabi frequencies. In the case of small RF Rabi frequencies ($\ll \gamma_a$), we predict that in the vicinity of the resulting ultra-narrow features, the probe beam would experience group velocities up to 100 times lower than otherwise possible in an identically configured system without the additional couplings.

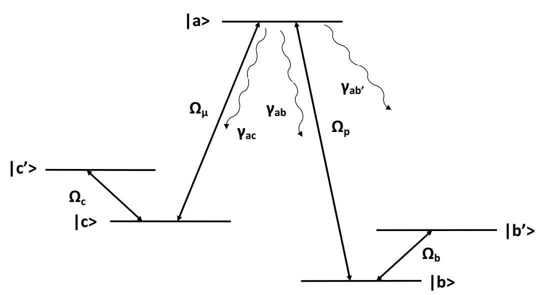

Figure 1: *Our model of a five level atomic system. Here Ω_μ is the strong control beam, and Ω_b and Ω_c are the Rabi frequencies of the new RF fields. The optical response of the system is probed by a laser with Rabi frequency Ω_p, near the $|b\rangle \to |a\rangle$ resonance.*

Non-Markovian quantum jumps

J. Piilo, S. Maniscalco, K. Härkönen, K.-A. Suominen

Department of Physics, University of Turku, FI-20014 Turun yliopisto, Finland

Open quantum systems that interact with structured reservoirs exhibit non-Markovian dynamics. We present a quantum jump method for treating the dynamics of such systems[1]. Our approach is a generalization of the standard Monte Carlo wave function (MCWF) method for Markovian dynamics[2]. The MCWF method identifies decay rates with jump probabilities and fails for non-Markovian systems where the time-dependent rates become temporarily negative. Our non-Markovian quantum jump (NMQJ) approach circumvents this problem, provides a simple unravelling of the ensemble dynamics with single histories, and gives interesting insight into the non-Markovian dynamics. To demonstrate our NMQJ method, we study a two-level atom in a photonic band gap material, see Fig. 1.

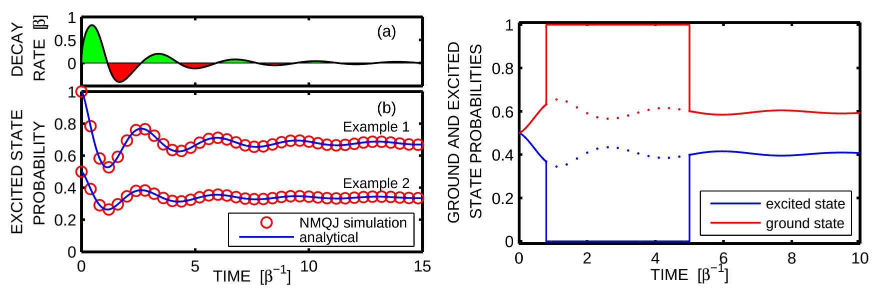

Figure 1: *The demonstration of the non-Markovian quantum jump (NMQJ) method with a two-level atom in a photonic band gap. In the left panel, the upper plot displays the time dependence of the decay rate with temporary negative values, and the lower plot shows the match between the analytical and the simulation results of the excited state dynamics. The right panel shows a single trajectory of the ensemble. Here, the first quantum jump occurs during the positive decay and destroys the superposition state of the two-level atom. The second jump happens when the decay rate has negative value, and this non-Markovian quantum jump restores the superposition which was lost in the earlier quantum jump.*

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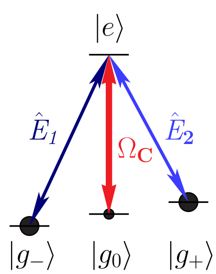
Storage and resonance retrieval of optical superposition states in an atomic medium

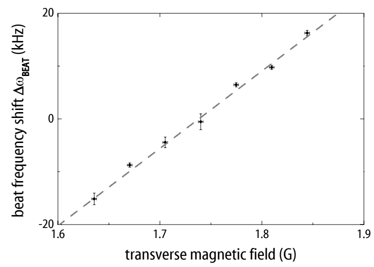
L. Karpa, F. Vewinger, M. Weitz

Institut für Angewandte Physik, Universität Bonn, Germany

Electromagnetically induced transparency (EIT) is a quantum interference effect that allows for the transmission of light through an otherwise opaque atomic medium[1]. Media exhibiting EIT have remarkable properties, as very low group velocities[2].
We investigate the storage of light in atomic rubidium vapor using a multilevel-tripod scheme as depicted in figure 1(a). As predicted in ref.3, in this system two optical modes propagating with a slow group velocity can exist[3]. In our experiment, which builds upon previous work[4,5], storage of light is performed by dynamically reducing the optical group velocity to zero. After releasing the stored pulse, a beating of the two reaccelerated optical modes is monitored. The observed beating signal oscillates at an atomic transition frequency, opening the way to novel quantum limited measurements of atomic resonance frequencies and quantum switches.



(a)



(b)

Figure 1: ***(a)*** *Tripod level scheme. The levels $|g_0\rangle$ and $|e\rangle$ are coupled by one strong control field with the Rabi frequency Ω_C while the two signal fields described by the quantum field operators $\hat{E}_1$ and $\hat{E}_2$ drive the transitions between $|g_-\rangle$ and $|e\rangle$ and $|g_+\rangle$ and $|e\rangle$ respectively. The dots are to indicate the ground state population.* ***(b)*** *Measured beat frequency of the released signal beams, after storage as a function of the applied (transverse) magnetic field. For all shown data points, the atomic sample was irradiated with optical signal fields of constant frequencies for each of the fields during the storage procedure.*

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[2] see e.g.: L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, Nature **397**, 594 (1999).
[3] D. Petrosyan and Y. P. Malakyan, Phys. Rev. A **70**, 023822 (2004).
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[5] L. Karpa and M. Weitz, New J. Phys. **10** (2008).

Coherent magnetic resonance spectroscopy of atomic hydrogen gas

L. Mazzola[1], K.-A. Suominen[1], A. Messina[2], S. Vasiliev[1]

[1]*Department of Physics, University of Turku, FI-20014 Turun yliopisto, Finland*
[2]*Dipartimento di Scienze Fisiche ed Astronomiche, Università di Palermo, 90123 Palermo, Italy*

Spin - polarized atomic hydrogen adsorbed on the surface of superfluid ^{4}He is an ideal realization of a two - dimensional weakly interacting boson gas which is expected to show collective quantum phenomena. Due to the reduced dimensionality, the achievement of high density, necessary condition for the appearance of collective phenomena, seems to be easier than in 3D case.

Recently measurements of the cold collision frequency shift in a doubly spin - polarized hydrogen gas adsorbed on the surface of a ^{4}He film has been realized in Turku [1]. During this experiment electron - nuclear double resonance (ENDOR) spectra were observed. At temperature T < 80 mK both absorption and dispersion ENDOR components exhibit an "exotic" behavior. The absorption spectrum has a dispersive line shape, whereas the dispersion spectrum looks like absorption. We explain these observations in terms of coherent interaction of electromagnetic excitation with hyperfine level system of H gas. This is the first demonstration of the electromagnetically induced transparency / absorption in magnetic resonance spectroscopy.

We have elaborated a theoretical model based on the density matrix equations of laser spectroscopy to predict and explain the observed lines. We schematize our atoms as three - level systems in ladder configuration, such that the first and second level are strongly coupled by resonance r.f. field, while the second and the third level are weakly coupled. To the usual linear equation pattern, containing terms describing populations and coherences decay and pumping, we have added some nonlinear terms. The idea of adding nonlinear terms arises from the necessity of considering two processes dramatically affecting the dynamics of the system, which are the three - body recombination, and the presence of the dipolar magnetic field. The latter is proportional to the gas density. The addition of nonlinear terms in the density matrix equations causes a wide spread of profiles in the theoretical ESR susceptibility components and with a proper setting of parameters we obtain theoretical curves matching the experimental ones.

[1] J. Ahokas, J. Järvinen and S. Vasiliev, Phys. Rev. Lett. 98 (2007) 043004

Spectral properties of systems exhibiting intrinsic optical bistability

M. G. Gladush, Vl. K. Roerich, A. A. Panteleev

State research center of the Russian Federation, Troitsk Institute for Innovation and Fusion Research, TRINITI, Troitsk, Moscow region, 142190 Russia

Alternative hypothetic mechanisms to give rise to intrinsic optical bistability are studied theoretically as the field-controlled switching between different spectral patterns of the probe beam absorption and fluorescent light. The spectra are calculated both analytically and numerically for the entire hysteresis loop of atomic excitation. The specroscopic analysis is likely to provide graphic distinction between alternative models describing similar hysteresis behaviours. The master equation and equations to find the spectral properties of the non-linear optical response are derived from the Bogolubov-Born-Green-Kirkwood-Yvon hierarchy for reduced single particle density matrices of two-level atoms and quantized field modes and their correlation operators. The hierarchy is treated in the limit of the polarization approximation to make a correct account for radiative relaxation of an atom in the surrounding medium.

Control of the Atom-Cavity Coupling Constant with a Nanopore Lattice in the Cavity-QED Microlaser

M. Lee[1], W. Seo[1], H.-G. Hong[1], Y. Song[1], W. Choi[2], R. R. Dasari[2], M. S. Feld[2], J.-H. Lee[1], K. An[1]

[1]*Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea*
[2]*G. R. Harrison Spectroscopy Laboratory, MIT, MA 02139, U.S.A.*

Although a uniform atom-cavity constant is assumed in almost all cavity quantum electrodynamics (QED) theories, atoms in an optical cavity in reality experience position-dependent coupling constants because of the standing-wave structure of the cavity mode. In this work, we have realized precisely controlled atom-cavity coupling constants for cavity QED experiments. We performed this feat by employing an atomic beam aperture[1] in the form of two-dimensional lattice of nanometer holes, i.e., nanopores, with a pitch of 791 nm, the same as the resonance wavelength of atomic barium, in front of the cavity in our cavity-QED microlaser[2]. When the horizontal position of the aperture is adjusted so as to make the vertical columns of nanopores aligned with the antinodes of the cavity, the atoms passing through the holes would experience the maximum coupling. On the contrary, if the columns of nanopores are aligned with the nodes of the cavity, the atom-cavity coupling would vanish. We have demonstrated the microlaser laser operation with adjustable atom-cavity coupling constants in this way. Our technique provides an opportunity to perform various cavity-QED experiments with continuously scannable atom-cavity coupling constants.

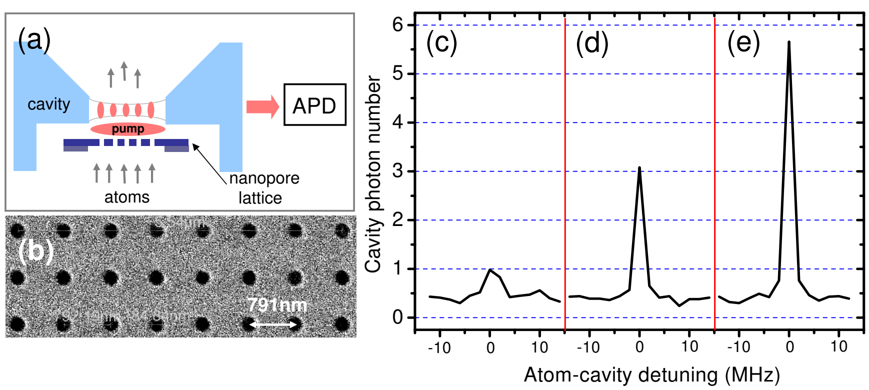

Figure 1: *(a) Experimental setup. (b) Focused ion beam image of the nanopore lattice. The pitch is about 791 nm coinciding with the resonant wavelength of the cavity (or atom), and the diameter is around 200 nm. Observed microlaser signal (mean number of photons in the cavity) when the atoms are localized (c) near the nodes, (d) in-between and (e) near the antinodes.*

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From a Single-Photon Source to a Single-Ion Laser

C. Russo[1], F. Dubin[1,3], H. Barros[1,2], A. Stute[1,2], C. Becher[1,4], P. O. Schmidt[1], R. Blatt[1,2]

[1] *Institut für Experimentalphysik, Universität Innsbruck, Austria*
[2] *Institut für Quantenoptik und Quanteninformation (IQOQI), Innsbruck, Austria*
[3] *Institute of Photonic Sciences (ICFO), Barcelona, Spain*
[4] *Fachrichtung Technische Physik, Universität des Saarlandes, Saarbrücken, Germany*

We study a single ^{40}Ca^{+} ion, confined in a linear Paul trap and coupled to a near-concentric high finesse optical cavity. A drive laser together with the cavity-mode excites an off-resonant Raman transition that connects the $S_{1/2}$ and $D_{3/2}$ levels of the ^{40}Ca^{+} ion (see Figure). Population gets transferred from $S_{1/2}$ to $D_{3/2}$ while emitting a photon into the cavity. The excitation cycle is closed by a recycling laser that brings the atomic population back to the initial state $S_{1/2}$ after spontaneous emission. Photons leaving the cavity are sent to a Hanbury-Brown&Twiss setup, where mean photon number and second order photon-photon correlations are measured.

In first experiments, we continuously excite the single-ion device and vary the intensities of the drive and recycling lasers. At low external pumping, the system evolves at the boundary of the strong coupling regime where we observe the signature of a quantum laser without threshold. On the other hand, for strong external pumping an intra-cavity photon number exceeding 0.3 is achieved, resulting in a substantial increase in stimulated emission of photons into the cavity. This resembles the mechanism for lasing in conventional lasers. Consequently, we observe threshold behavior of our single-ion device in this regime.

In another experiment, we generate single photons on demand by applying pulsed excitation to the ion. We first generate a photon in the cavity mode by a pulse of the drive laser. The emitted photon subsequently leaves the cavity and the ion is projected onto the $D_{3/2}$ state. A recycling pulse then excites the ion to the $P_{1/2}$ state from which it decays back to the $S_{1/2}$ state. This reinitializes the system and the sequence is repeated. The resulting second order photon-photon correlations reveal the high efficiency of such a single-photon source and agrees with theoretical simulations of the process.

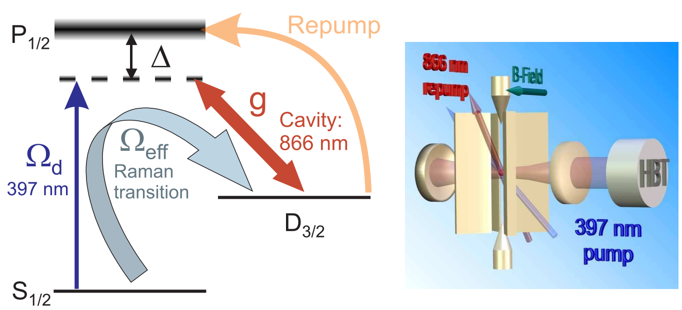

Figure 1: *A single ^{40}Ca^{+} ion coupled to a high-finesse cavity.* ***Left:*** *Level and excitation scheme.* ***Right:*** *Schematic experimental setup.*

Strong magnetic coupling between an electronic spin qubit and a mechanical resonator

P. Rabl[1,2], M. D. Lukin[1,2]

[1] *Institute for Theoretical Atomic, Molecular and Optical Physics, Cambridge, MA 02138, USA*
[2] *Physics Department, Harvard University, Cambridge, MA 02138, USA*

Techniques for cooling and manipulating motional states of a nano-mechanical resonator are nowadays actively explored, motivated by ideas from quantum information science, testing quantum mechanics for macroscopic objects and potential applications in nano-scale sensing. Here we describe a technique that enables a coherent coupling between a single electronic spin qubit associated with a nitrogen-vacancy impurity in diamond and the quantized motion of a nano-mechanical resonator. The basic idea can be understood from the prototype system shown in Fig. (1). Here a single spin is used to sense the motion of the magnetized, vibrating tip, that is separated from the spin by an average distance $h \approx 25 - 50$ nm. Oscillations of the tip produce a time-varying magnetic field that causes Zeeman shifts of the spin qubit. Under realistic conditions the shift corresponding to a single quantum of motion can approach 100 kHz and exceed both the electronic spin coherence time ($T_2 \sim 1$ ms) and the intrinsic damping rate, $\kappa = \omega_r/Q$, of high-Q mechanical resonators. In this regime, the spin becomes strongly coupled to mechanical motion in direct analogy to strong coupling of cavity QED.

We describe how this regime can be achieved in a practical setting specifically addressing the issues of fast dephasing ($T_2^* \sim 1\,\mu$s) of the electronic spin due to interactions with the nuclear spin bath. Under such conditions strong coupling can be achieved by a careful preparation of dressed spin states which are highly sensitive to the motion of a magnetic resonator but insensitive to perturbations from the nuclear spin bath. In combination with optical pumping techniques, the coherent exchange between spin and motional excitations enables ground state cooling and the controlled generation of arbitrary quantum superpositions of resonator states. In addition, optical spin readout techniques provide a general measurement toolbox for the resonator mode with quantum limited precision.

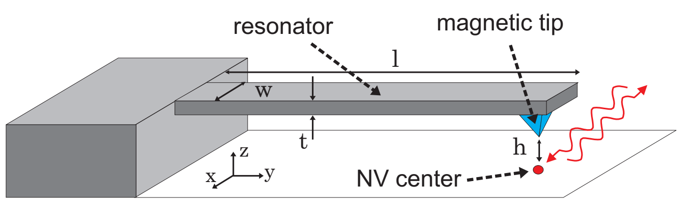

Figure 1: *A magnetic tip attached to the end of a nano-mechanical resonator of dimensions* (l, w, t) *is positioned at a distance* $h \sim 25$ *nm above a single NV center, thereby creating a strong coupling between the electronic spin of the defect center and the motion of the resonator. Microwave and laser fields are used to manipulate and measure the spin states.*

Interaction between neutral atoms and superconducting surfaces

R. Fermani, S. Scheel, E. A. Hinds, P. L. Knight

Quantum Optics and Laser Science, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BW

An atom close to a dielectric or metallic surface experiences magnetic field fluctuations arising from thermally-induced noise currents. The origin of those noise currents is connected with the finite resistivity and the skin depth of the substrate.

The use of superconducting films has been proposed as a way to reduce thermally-induced noise[1]. As the resistance of a superconductor is ideally zero, there should be no thermally-induced noise and the cryogenic temperature would help to reduce heating and background collisions. However, most practical applications of superconductivity demonstrate that dissipation phenomena can take place in superconductors. In particular, thin superconducting films can be regarded as two-dimensional (2D) systems where fluctuations resulting from bulk losses seem to be negligible and the dominant noise source is given by vortex motion.

Neutral atoms are shown to be ideal candidates to probe the magnetic field due to vortices in thin superconducting films close to the Kosterlitz-Thouless-Berezinskii transition temperature. The relaxation time T_1 of the Zeeman sublevel populations, (due to thermally induced spin-flip transitions), and the transverse relaxation time T_2 for Zeeman coherences are shown to be very useful in the study of the vortex dynamics[2].

Moreover, the relaxation time T_1 depends on physical parameters such as the penetration depth, the thickness of the superconducting layer and the atom-surface distance. The lifetime T_1 has been calculated for a d-wave superconductor which has an anisotropic penetration depth. The analysis of such lifetime allows to define a screening factor as a function of the layer thickness which can be compared with the case of a half planar metal.

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Strong coupling of single optical emitters to nano-scale surface plasmons

B. J. Shields[1], A. V. Akimov[1,2], A. S. Zibrov[1], D. E. Chang[1], F. H. L. Koppens[1], C. L. Yu[3], H. Park[3], P. R. Hemmer[1,4], M. D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2]*P. N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, 119991, Russia*
[3]*Department of Chemistry, Harvard University, Cambridge, MA 02138, USA*
[4]*Electrical Engineering Department, Texas A&M University, College Station, TX 77843, USA*

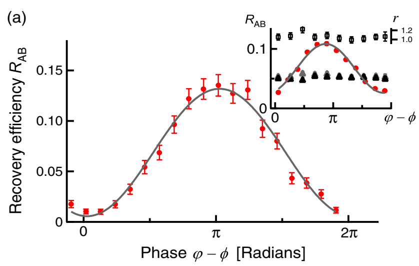
We present an experimental observation of strong optical coupling between individual, nanocrystal CdSe/ZnS quantum dots, as well as Nitrogen-Vacancy color centers in diamond nanocrystals, and the guided surface plasmon modes of a proximal silver nanowire. The strong coupling between emitter and field is enabled by the unique properties of the plasmon modes on these nanowires. In particular, due to the small size of the nanowires ($\sim$100 nm in diameter), the surface plasmons are localized transversely to dimensions well below the diffraction limit. An enhancement of the Purcell factor of the system and photon correlations consisten with a single-photon source are observed, and a realistic theoretical model for these processes is presented.

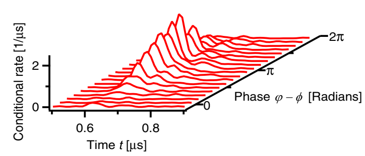
Single-Photon Bus between Spin-Wave Quantum Memories

J. Simon[1,2], H. Tanji[1,2], S. Ghosh[2], V. Vuletić[2]

[1] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

Generation of non-classical correlations (entanglement) between atoms [1] photons [2], or combinations thereof[3], is at the heart of quantum information science. Of particular interest are material systems serving as quantum memories that can be interconnected optically[4] An ensemble of atoms can store a quantum state in the form of a quantized collective spin excitation (magnon), that can be mapped onto a photon[5] with high efficiency [6]. Here we report the phase-coherent transfer of a single magnon from one atomic ensemble to another via an optical resonator serving as a quantum bus that in the ideal case is only virtually populated. Partial transfer deterministically creates an entangled state with one excitation jointly stored in the two ensembles. The entanglement is verified by mapping the magnons onto photons, whose correlations can be directly measured. These results will enable deterministic multipartite entanglement between atomic ensembles.





(c)

p_{00}	p_{10}	p_{01}	p_{11}
0.88(1)	0.08(1)	0.030(4)	0.0005(2)

Figure 1: *(a) Recovery efficiency of joint readout of two ensembles, versus readout phase difference. High contrast sinusoidal variation indicates large degree of coherence between the two samples. Inset: Recovery efficiencies of samples read out individually. (b) Time dependence of readout, versus readout phase. (c) Table of all non-negligible diagonal elements of system density matrix, indicating supression by a factor of 4 of two-magnon events.*

[1] Matsukevich *et. al.*, Phys. Rev. Lett. **96** 030405 (2006); Chou *et. al.*, Nature **438**, 837 (2005).
[2] Marcikic *et. al.*, Phys. Rev. Lett. **93** 180502 (2004)
[3] Blinov *et. al.*, Nature **428** 153 (2004); Matsukevich *et. al.*, Phys. Rev. Lett. **95** 040405 (2005).
[4] Julsgaard *et. al.*, Nature **413** 400 (2001).
[5] Duan *et. al.*, Nature **414** 413 (2001); Black *et. al.*, Phys. Rev. Lett. **95**, 133601 (2005); Thompson *et. al.*, Science **313**, 74 (2006); Chaneliere *et. al.*, Nature **438** 833 (2005)
[6] Simon *et. al.*, Phys. Rev. Lett. **98** 183601 (2007)

Single Atom and Photon Interactions Using a Toroidal Microresonator: A Photon Turnstile

S. Kelber[1], B. Dayan[1], Takao Aoki[1], A. Parkins[2], E. P. Ostby[1], K. J. Vahala[1], H. J. Kimble[1]

[1]*California Institute of Technology, Pasadena, CA 91125, USA*
[2]*Department of Physics, University of Auckland, Auckland, New Zealand*

Significant advances in quantum information science have been achieved through matter systems that mediate single photon interactions.[1] In this contribution we demonstrate the use of a microtoroidal optical resonator to achieve a robust, efficient mechanism for regulating the transport of photons one by one. We also use computer simulations to examine the effect of surface-induced van der Waals forces on our atom-cavity system.

In our experiments we monitor the effect of single CS atoms transiting close to a microtoroid critically coupled to a tapered fiber. As opposed to the strong coupling regime where the atom-cavity coupling rate, $\underline{g}$, dominates all other dissipation rates, we operate in the so called 'bad-cavity' limit where the coupling of the cavity to the input-output modes dominates ($\kappa \gg \underline{g}$). The atoms interact with the fields of the resonator and regulate photon statistics by means of an interference effect involving the directly transmitted optical field, the intracavity field in the absence of the atom, and the polarization field radiated by the atom.[2] Photon counting measurements verify the transformation from a Poissonian to a sub-Poissonian photon stream. This dynamical mechanism to create the photon turnstile requires only that the intracavity atomic absorption be large and is thus robust against experimental variations in the atom-cavity coupling.

Additionally, numerical simulations modeling surface-induced van der Waals interactions between the toroids and Cs atoms indicate that these forces reduce the effective atom coupling, $\underline{g}_{eff}$, by $\sim$2x. These results serve as a guide for future experiments that could directly probe surface interactions or investigate the possibility of atom trapping near the toroid surface.

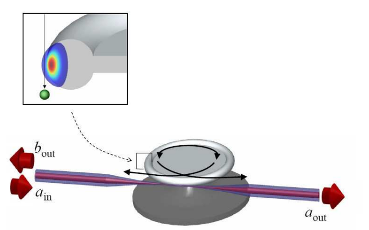


Figure 1: *A schematic of the experimental setup showing the microtoroid coupled to the tapered fiber and the associated input and output modes. Falling Cs atoms passing close enough to the toroid interact with the evanescent field (inset).*

[1]H.J. Kimble,"The Quantum Internet.", Nature Insight Review (2008).
[2]Dayan et. al., Science **319**, 1062 (2008).

Protecting entanglement via the quantum Zeno effect

S. Maniscalco[1], F. Francica[2], R. L. Zaffino[2], N. Lo Gullo[2], F. Plastina[2]

[1]*Department of Physics, University of Turku, FI-20014 Turku, Finland*
[2]*Dip. Fisica, Università della Calabria, & INFN - Gruppo collegato di Cosenza, 87036 Arcavacata di Rende (CS), Italy*

Entanglement is a quantum correlation between two or more parts of a composite quantum system. Erwin Schrdinger described it as "the characteristic trait of quantum mechanics, the one that entails its entire departure from classical lines of thought". During the last few decades the potential of entanglement for new quantum technologies has been explored, paving the way to new areas of physics combining information theory and communication technology with quantum mechanics.
Entanglement is, however, a very delicate property. Any interaction of quantum systems with their environment inevitably destroys it. Since no quantum system is completely isolated from the external environment, the preservation of entanglement may seem an insurmountable problem.
We have demonstrate that entanglement can be effectively protected from the harming effects of the environment by using a purely quantum phenomenon, known as the quantum Zeno effect. The quantum Zeno effect states that repeated and frequent measurements of the state of a quantum system, aimed at checking whether the system is still in its initial state or not, may freeze its dynamics [1]. As the saying goes "A watched pot never boils".
Interestingly enough a similar conclusion holds if appropriate measurements are performed on the environment rather than on the system itself. Our results demonstrate that the entanglement of two quantum bits (qubits) can be protected from entanglement deterioration simply by monitoring the environment. Instead of watching the pot we watch the stove flame. Specifically we consider two entangled atoms in a lossy cavity and we prove that monitoring the cavity field leads to entanglement protection [2].

[1]B. Misra and E.C.G. Sudarshan, J. Math. Phys. **18**, 756 (1977)
[2]S. Maniscalco, F. Francica, R. L. Zaffino, N. Lo Gullo, and F. Plastina, Phys. Rev. Lett. **100**, 090503 (2008)

Polarity manipulation of Atom-Cavity Coupling Constant in the Cavity-QED Microlaser

W. Seo[1], H.-G. Hong[1], M. Lee[1], Y. Song[1], W. Choi[2], R. R. Dasari[2], M. S. Feld[2], J.-H. Lee[1], K. An[1]

[1]*Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea*
[2]*G. R. Harrison Spectroscopy Laboratory, MIT, MA 02139, U.S.A.*

In the study of cavity quantum electrodynamics (QED) only the absolute value of atom-cavity coupling constant has been considered since in all of the experiments so far such as cold single atoms in a cavity[1] the coupling constant is treated as unipolar. In the present study, we ask what happens if the coupling constant is bipolar in the cavity-QED microlaser.[2] Obviously, if the coupling constant changes its sign once in an anti-symmetric way during the atom-cavity interaction time τ, the pulse area of the cavity field seen by the atom would be zero, and thus a lasing would not occur. We show, however, that a maximum gain can be achieved with a proper atom-cavity detuning in this case. In our experiment performed with a TEM_{10} cavity mode interacting with the $^1\mathrm{S}_0$-$^3\mathrm{P}_1$ transition (791 nm) of atomic barium, we observed a minimum lasing on resonance whereas a maximum lasing occurs when the detuning is equal to $1/(\sqrt{2}\tau)$. Our results can be well explained in terms of semiclassical Bloch vector picture.

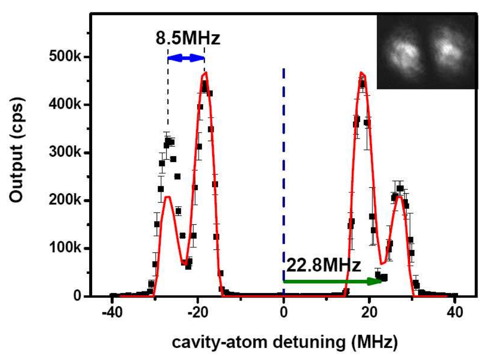


Figure 1: *Cavity-QED microlaser output versus atom-cavity detuning for a* TEM_{10} *mode. Solid line is a fit curve based on a semiclassical microlaser theory. The signal at detuning of* $\pm$*22.8 MHz corresponds to on-resonance condition, exhibiting a minimum lasing signal. The separation between two peaks around the minimum point is 8.5 MHz, consistent with theoretical prediction. The inset is the far-field image of the output signal.*

[1]G. R. Guthöhrlein et al., Nature **414**, 49 (2001);P. Maunz et al., Opt. Lett. **28**, 46 (2003);T. Puppe et al., Phys. Scr. **T112**, 7 (2004);S. Nußmann et al., Phys. Rev. Lett. **95**, 173602 (2005);T. Puppe et al., Phys. Rev. Lett. **99**, 013002 (2007).

[2]K. An, J. J. Childs, R. R. Dasari, and M. S. Feld, Phys. Rev. Lett. **73**, 3375 (1994); W. Choi et al., Phys. Rev. Lett. **96**, 093603 (2006).

Coherent Manipulation of Single Atoms in Cavity QED

S. Kim, C. Shih, M. Gibbons, P. Ahmadi, M. Chapman

[1] *Department of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA*

Cavity QED systems consisting of neutral atoms coupled to high finesse optical microcavities have important applications to quantum information processing and communication. We have developed an experimental apparatus with trapped atoms in a high finesse cavity in the strong coupling regime. We have demonstrated deterministic loading and storage of individual atoms delivered from a magneto-optic trap to the resonator using an atom conveyor [1].

In this poster, we present our progress towards realizing a two atom quantum gate utilizing dual neutral atom registers in a high finesse optical cavity. The framework for achieving this goal is to have the ability to couple two atoms to the same cavity mode via individual conveyors with independent control which can be seen in Fig. 1.

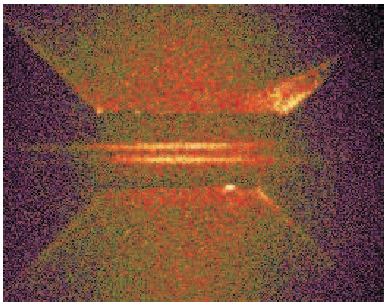


Figure 1: *Florescence image of two lattices between two cavity mirrors.*

Our endeavors have branched out to indepth studies of the optical lattice. Noise measurements have shown that lifetimes are limited by instabilities in the axial direction of the trapping potential. With continuous cooling, lifetimes are extended from 60 s to 300 s, limited only by background collisions.

[1] K. Fortier, S. Kim, M. Gibbons, P. Ahmadi, M. Chapman, Phys. Rev. Lett. **98**, 233601 (2007).

Restoring the wave function with Cavity QED of single Yb atoms

N. Takei[1], M. Takeuchi[1], M. Ueda[1,2], M. Kozuma[1,3]

[1] *ERATO Macroscopic Quantum Control Project, JST, Tokyo, Japan*
[2] *Department of Physics, University of Tokyo, Tokyo, Japan*
[3] *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*

Quantum measurement, i.e., non-unitary process, has been believed to be irreversible. However, Royer found a method of restoring the wave function even after the measurement process[1,2]. Such a measurement can be implemented for single 1/2 spins by using Faraday rotation[3]. Since the information on the spin direction can be extracted through the Faraday rotation of optical probe pulses, the spin state changes in a non-unitary manner. However, if the rotation angle is small (measurement is weak), successive measurements probabilistically cancel the measurement effect and the premeasurement state is restored completely.

To implement such a reversible measurement, the detection of Faraday rotation due to a single 1/2 spin is inevitable, that is, a cavity QED system is required. Here we report on real-time detection of single Yb atoms with a cavity QED system, which is the first step to realize the reversible measurement. The Yb atoms have several merits for the spin manipulation, one of which is a longer coherence time compared with alkali-atoms. This is because the ground state of Yb atoms is diamagnetic, and the magnetic moment has its origin only in nuclear spin. We select the ^{171}Yb isotope, which posseses 1/2 nuclear spin.

The outline of our experiment is as follows: we first trap Yb atoms in a magneto-optical trap (Upper MOT) with $^1S_0$-$^3P_1$ intercombination transition (556nm). Atoms released from the upper MOT are recaptured with the lower MOT which is located just above a high-finesse Fabry-Perot cavity. Ultraslow atoms are dropped into the cavity and their transits are detected. Our cavity shows the finesse of about 1×10^5 at 556nm, and the cavity length is stabilized at 150 μm. The resulting atom-cavity coupling g, the cavity-field decay rate κ, and the dipole decay rate γ are $(g, \kappa, \gamma)/2\pi$=(2.8, 4.8, 0.09) MHz, respectively. In the presentation we will also report the observation of Faraday rotation with single Yb atoms.

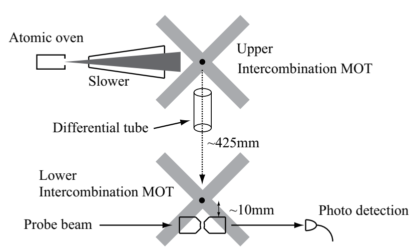


Figure 1: *Schematic diagram of the experiment.*

[1] M. Ueda and M. Kitagawa, Phys. Rev. Lett. **68**, 3424 (1992).
[2] A. Royer, Phys. Rev. A **73**, 913 (1994).
[3] H. Terashima and M. Ueda, Phys. Rev. A **74**, 012102 (2006).

Precessing magnon as a heralded quantum memory for photon polarization states

H. Tanji[1,2], S. Ghosh[2], J. Simon[1,2], V. Vuletić[2]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

A collective excitation of an atomic ensemble (a magnon) may be strongly coupled to a single mode of the electromagnetic field. This makes a magnon an ideal format with which to store a photonic quantum state; the conversion to and from a photon is facilitated by the collective strong coupling. Single excitations have routinely been stored as magnons and retrieved as single photons after a programmable delay[1]. Transfer of a magnon from one atomic ensemble to another via an optical resonator has also been demonstrated[2]. The versatility of the system, however, is limited by restrictions on accessible photon polarization states due to the phase matching requirement necessary for strong coupling. Here we demonstrate the precession of a magnon state which removes such restrictions and, using this technique, realize a heralded quantum memory for arbitrary (unknown) polarization states. We optically pump an ensemble in a rotating frame and generate a precessing magnon that corresponds to the input polarization state. The stored state is later recovered in the form of a single photon with a state-independent polarization fidelity of $90(2)\%$. The single photon nature of the recovered photons is confirmed by a conditional autocorrelation measurement yielding $g_2 = 0.24(5)$, a four-fold suppression of two-photon events compared to a Poisson distribution. The quantum memory demonstrated here may serve as one of the key building blocks for distributed quantum networks and quantum computers.

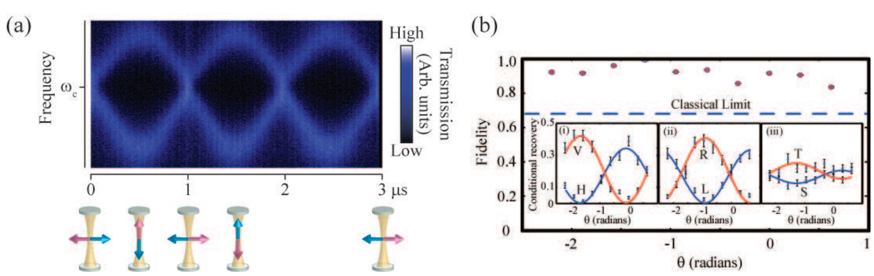


Figure 1: *(a) The precession of the ensemble is observed as a variation of the vacuum Rabi splitting in the transmission spectrum of a weak probe beam through the optical resonator. (b) The polarization fidelities for different input states* $|\psi\rangle = \cos(\theta + \frac{\pi}{4})\,|R\rangle + e^{i\phi}\sin(\theta + \frac{\pi}{4})\,|L\rangle$ *for a fixed* ϕ*, calculated from the projection of output states in three orthogonal bases, H-V, L-R, and S-T (insets i, ii, and iii, respectively).*

[1]A. Kuzmich *et. al.*, Nature **423**, 731 (2003); M. D. Eisaman *et. al.*, Nature **438**, 837 (2005); J. Simon *et. al.*, Phys. Rev. Lett. **98**, 183601 (2007).
[2]J. Simon *et. al.*, Nature Physics **3**, 765 (2007).

Observation of atom-cavity interaction with cold single atoms with various coupling constants

Y. Choi, S. Kang, S. Lim, J.-H. Lee, K. An

Department of Physics and Astronomy, Seoul National University, Seoul, 151-747, Korea

Exceptional point(EP) where the energy-level crossing and avoided crossing coalesce has drawn much interest in the study of quantum systems described by non-Hermitian Hamiltonian.[1] Atom-cavity system with non-negligible damping is also described by non-Hermitian Hamiltonian, and thus it is of considerable interest to observe an EP and to explore possible non-singular atom-cavity interaction around the EP. Toward this end, we have devised ways to vary the coupling constant g between the atom and the cavity in order to achieve EP condition $g = |\gamma_c - \gamma_p|/2$, where $2\gamma_c$ is the cavity decay rate and γ_p is the half width of the atomic transition. For the maximum coupling constant g_0 achieved in our experiment with atomic rubidium, relevant parameters were $(g_0/2\pi, \gamma_c/2\pi, \gamma_p/2\pi)$=(16, 19, 3) MHz for a cavity with a finesse of 25000 and a length of 155 μm, and thus the strong coupling condition, $g > |\gamma_c - \gamma_p|/2$, was satisfied. We could change the coupling constant by selecting either σ or π atomic transition or by employing various TEM$_{n,m}$ cavity modes. The atomic transition was selected by the polarization of a probe laser for cavity transmission measurement while single atoms dropped from a MOT just above the cavity were traversing the cavity.[2] So far, we have realized the coupling constant down to $g = 0.76g_0$. We plan to investigate the atom-cavity system across the EP condition($g_{EP} = 0.5g_0$) by employing high-order TEM modes.

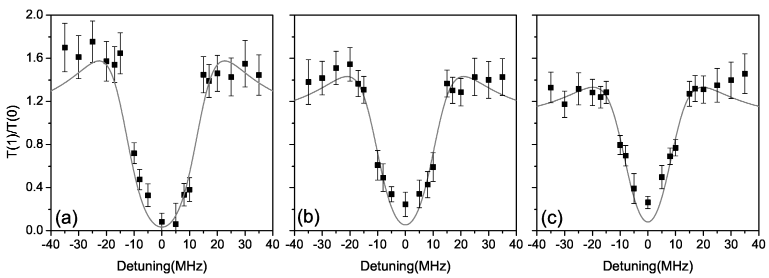


Figure 1: *Transmittance of a cavity coupled with a single rubidium atom. (a) With TEM$_{00}$ mode and σ^+ polarization for the probe. Coupling constant takes a maximum value, $g = g_0$. (b) TEM$_{10}$ mode with σ^+ polarization give $g = 0.86g_0$ due to increased mode volume. (c) TEM$_{00}$ with π polarization result in $g = 0.76g_0$ due to decreased transition strength. The transmittance for a single atom $T(1)$ is normalized with respect to the empty cavity transmittance $T(0)$. The sold curves are theoretical predictions without adjustable parameters.*

[1] W. D. Heiss et al., J. Phys. A: Math. Gen., **23** 1167 (1990).
[2] H. Mabuchi et al., Opt. Lett. **21**, 1393 (1996).

Dynamical Casimir Effect for Two Oscillating Mirrors in 3-D

Cem Yuce, Zalihe Ozcakmakli

Department of Physics, Anadolu University, Eskisehir, Turkey

The generation of photons in a three dimensional rectangular cavity with two moving boundaries is studied by using the Multiple Scale Analysis (MSA). It is shown that number of photons are enhanced for the cavity whose walls oscillate symmetrically with respect to the center of the cavity. The non-stationary Casimir effect is also discussed for the cavity which oscillates as a whole.

Poster Session II

Tuesday, July 29
4:15 pm – 6:00 pm
Wilbur Cross Building, Reading Rooms

Precision Measurements and Fundamental Constants

Atomic Interactions and Collisions

Cooling and Trapping

Fermi Gases

Mesoscopic Quantum Systems

A Supersonic Gas Jet Seeded with Tungsten Atoms

J. Lee[1], R. Paudel[2], A. E. Leanhardt[1]

[1]*Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA*
[2]*Department of Physics, Wabash College, Crawfordsville, IN 47933, USA*

We report on progress towards making a continuous tungsten carbide (WC) molecular beam for an electron electric dipole moment (EDM) search. WC has a $^3\Delta_1$ ground state with its two valance electrons in a $\sigma\delta$ molecular orbital configuration[1,2,3]. This molecular structure has been shown to have several unique advantages for an electron EDM search[4].
At present, we have successfully seeded a supersonic gas jet with tungsten atoms. A tungsten filament is resistively heated to over 3000 K in the presence of an argon buffer gas. The resulting W vapor is entrained in a supersonic jet formed by allowing the argon gas to flow through a conical nozzle into vacuum. At low argon pressures, we verify the presence of tungsten in the beam with a quadrupole mass spectrometer [Fig. 1(a)]. At high argon pressures, we directly observe the beam profile by allowing the Ar + W supersonic jet to sputter onto a copper foil placed downstream from a skimmer [Fig. 1(b)].

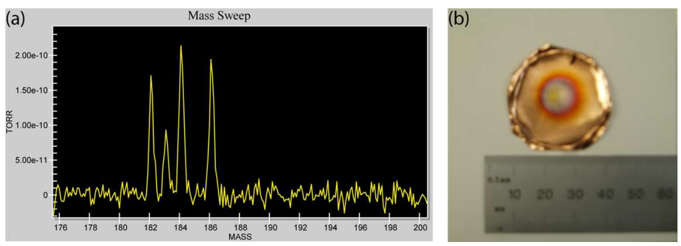


Figure 1: *Tungsten atomic beam diagnostics. (a) Quadrupole mass spectrum of W isotopes evaporated from a filament. (b) Ar + W supersonic beam sputtered onto a copper foil placed* ~ 25 *cm downstream from a* 3 *mm diameter skimmer.*

Future work will focus on optical spectroscopy of metastable argon and tungsten atoms in the jet. Additionally, we plan to add a small fraction of methane to the carrier gas and search for tungsten carbide molecules formed through the reaction $\mathrm{W} + \mathrm{CH}_4 \rightarrow \mathrm{WC} + 2\mathrm{H}_2$, which has been observed previously[3].

[1]X. Li, S.S. Liu, W. Chen, and L.-S. Wang, J. Chem. Phys. **111**, 2464 (1999).
[2]K. Balasubramanian, J. Chem. Phys. **112**, 7425 (2000).
[3]S.M. Sickafoose, A.W. Smith, and M.D. Morse, J. Chem. Phys. **116**, 993 (2002).
[4]E.R. Meyer, J.L. Bohn, and M.P. Deskevich, Phys. Rev. A **73**, 062108 (2006).

Search for the electron’s electric dipole moment with cold ThO molecules

A. C. Vutha[1], O. K. Baker[1], W. C. Campbell[2], J. M. Doyle[2], G. Gabrielse[2], Y. V. Gurevich[2], P. Hamilton[1], N. Hutzler[2], M. A. H. M. Jansen[2], D. DeMille[1]

[1]*Department of Physics, Yale University, New Haven, CT 06511, USA*
[2]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*

The CP-violating electric dipole moment (EDM) of the electron has remained elusive in spite of over 50 years of experimental efforts. A nonzero EDM would provide an unambiguous signature of phenomena beyond the Standard Model of particle physics. The metastable H state in thorium monoxide (ThO) has been identified as a system that is highly sensitive to an electron EDM. The H state in ThO also has exceptional properties for the rejection of systematic errors that are known to affect molecular beam EDM measurements. We describe an experiment that is in progress, using a cryogenic source of ThO molecules, to measure the precession of an EDM-induced molecular dipole in an electric field. We discuss recent measurements of the production of a cold ThO beam and a measured bound on the radiative lifetime of the H state. Based on these preliminary results, we expect that this system could substantially improve the experimental sensitivity to an electron EDM.

Dispelling the curse of the neutron skin in atomic parity violation

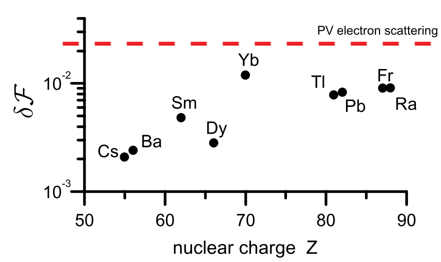
B. A. Brown[1], A. Derevianko[2], V. V. Flambaum[3]

[1]*Department of Physics and Astronomy, and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[2]*Department of Physics, University of Nevada, Reno, Nevada 89557,USA*
[3]*School of Physics, University of New South Wales, Sydney 2052, Australia*

Atomic parity non-conservation (PNC) provides powerful constraints on extensions to the standard model of elementary particles. In such measurements one determines a parity-violating signal $E_{\rm PNC}$, related to the quantity of interest, the weak charge, Q_W, as $E_{\rm PNC} = k_{\rm PNC}\, Q_W$. The coefficient $k_{\rm PNC}$ comes from atomic calculations. Considering challenges faced by such calculations, an alternative approach is to form a ratio $\mathcal{R}$ of the PNC amplitudes for two isotopes of the same element[1]. Since the factor $k_{\rm PNC}$ remains the same, it cancels out in the ratio.

However, a limitation to this approach was pointed out[2] – an enhanced sensitivity of possible constraints on "new physics" to uncertainties in the neutron distributions. This problem is usually referred to as the problem of the neutron "skin", i.e., the uncertainty brought in by the difference in the nuclear proton and neutron distributions. Here we show that the neutron skins in different isotopes are correlated; this leads to a substantial cancelation in the neutron skin induced uncertainties in the PNC ratios. In the figure, the resulting neutron-skin-induced uncertainties for isotopic chains are compared to the relevant constraints on "new physics" from parity-violating electron scattering (PVES). It is clear that all isotopic-chain determinations are competitive to bounds derived from PVES. For example, measurements with isotopes of Cs, Ba and Dy would be an order of magnitude more sensitive to the new physics.

Details can be found in arXiv:0804.4315. This work was supported in part by NSF, US DoS Fulbright fellowship, and ARC.



[1]V. A. Dzuba, V. V. Flambaum, and I. B. Khriplovich, Z. Phys. D **1**, 243 (1986)
[2]E.N. Fortson et al., Phys. Rev. Lett. **65**, 2857 (1990)

Characterization of an high precision cold atom gyroscope

A. Landragin, A. Gauguet, T. Leveque, W. Chaibi

LNE-SYRTE, CNRS UMR 8630, UPMC, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France

We present the full characterization of our cold atom gyroscope-accelerometer. This experiment has been designed to give access to all six axes of inertia[1] (the three accelerations and the three rotations axes) in a relatively compact system. The results, presented here, show the limits of the performances of this first cold atom gyroscope and how to overcome them. This study can be used as a guideline for the design and the optimization of high performance inertial sensors based on atom interferometry such as gyroscopes, accelerometers and gradiometers, which are envisaged for applications in inertial navigation, geophysics and tests of general relativity.

Caesium atoms are loaded from a vapour into two independent magneto-optical traps for 140 ms. Two caesium clouds are then launched into two opposite parabolic trajectories using moving molasses at 2.4 $m.s^{-1}$, with an angle of 8° with respect to the vertical direction. At the apex of their trajectory, the atoms interact successively with three Raman laser pulses, which act on the matter-wave as beam splitters or mirrors, and generate an interferometer of 80 ms total interaction time. The use of two atomic sources allows discrimination between the acceleration and rotation.

The sensitivity to acceleration is $5,5 \times 10^{-7} m.s^{-2}$ at one second, limited by residual vibration on our isolation platform. Concerning the rotation, the sensitivity is $2,3 \times 10^{-7} rad.s^{-1}$ at one second, limited by the quantum projection noise in the detection. After 1000 seconds of integration time, we achieve a sensitivity of $1 \times 10^{-8} rad.s^{-1}$. Moreover, we have extensively studied possible sources of shift on the rotation signal. Among others, we have measured the effect of the two photons light shift induced by off-resonant Raman transitions. We also identified the main limit to the stability, which is linked to fluctuations of the atomic trajectories inducing Raman laser wave-front changes.

We characterize the accuracy of our gyroscope in term of bias and scaling factor. For this purpose, we have measured rotation phase shift as a function of the interrogation time and rotation rate. As expected, the rotation shift scales as the square of the interrogation time and linearly with the projection of the Earth's rotation rate, which is modulated by turning the interferometer in the horizontal plane. Linearity of our sensor is demonstrated at the 10^{-4} level. This allows to determine the bias with an accuracy of $5 \times 10^{-8} rad.s^{-1}$.

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Light shift of the 6S-8S two-photon transition in cesium

Yi-Chi Lee[1], Ying-Yu Chen[2], Yi-Hsiu Chang[2], Hsiang-Chen Chui[1], Chin-Chun Tsai[1,2]

[1]*Institute of Electro-Optical Science and Engineering, National Cheng-Kung University, Tainan, Taiwan 70101*
[2]*Department of Physics, National Cheng-Kung University, Tainan, Taiwan 70101*

We measured the light shift of the 6S-8S two-photon transition in cesium by comparing the frequency shift in two separated temperature stabilized glass cells. Two cells, REF and MAIN, were heated and temperature stabilized to around 45±0.1^{o}C. A cw single mode Ti:sapphire laser($\triangle\nu \sim 500kHz$) was tuned at 822nm to excited the cesium atoms from 6S to 8S by two-photon transition. A beam-splitter picks up about 20mW(fixed) of the laser power and directs into the REF cell while the rest of the laser power is varied by a set of neutral density filters and then directs through the MAIN cell. Both cells are inside a confocal lens system by reflecting the incident beam back. An violet fluorescence cascade from Cs(7P to 6S, and 7P was populated by spontaneous emission from 8S) was monitored by a filtered-PMT from both cells simultaneously (as shown in Figure 1). Fitting signals to the Lorentzian profile one can obtain the spectrum linewidth (FWHM is about 2 MHz) and the center frequency deviations between the REF and MAIN cells with varies laser power on MAIN cell. Light shift and laser power broadening of the 6S-8S two-photon transition in cesium will be discussed[1].

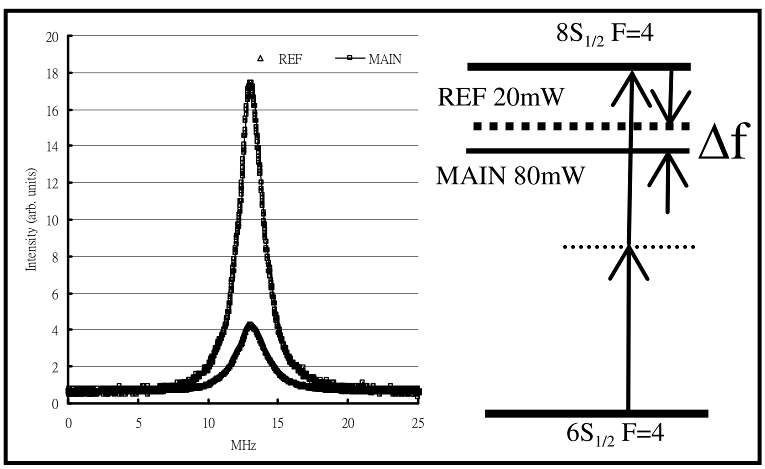

Figure 1: *Left: Violet fluorescence from Cs(7P→6S) in both REF and MAIN cells were monitored by a filtered-PMT simultaneously. Right: The relative energy positions indicate the Cs 6S-8S two-photon transition and light shift for different laser power (not to scale).*

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Precise Measurement of the Isotope Shift of the Lithium D Lines

C. E. Simien, J. D. Gillaspy, Craig J. Sansonetti

National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

High precision spectroscopy of transitions between low-lying levels of lithium has been proposed[1] and used[2] as a means for determining the nuclear radii of various lithium isotopes. The method is premised on the expectation that isotope shifts for these transitions can be calculated with sufficient accuracy that the nuclear radius is the dominant contributor to any observed discrepancy between theory and experiment. The possibility of determining nuclear radii by laser spectroscopy is of particular interest for the short-lived exotic isotopes ^{8}Li, ^{9}Li and ^{11}Li.
Despite several recent experiments, however, measured isotope shifts for the resonance lines of the stable isotopes ^{6}Li and ^{7}Li remain in strong disagreement with each other and with theory.[3,4,5,6,7] The discrepancy between theory and experiment for the splitting isotope shift (SIS), the difference between the isotope shifts of the D_1 and D_2 lines, is of particular concern. The SIS is thought to be the most reliable result of theory because it is largely independent of QED and nuclear size effects.[8] Currently the most precise reported measurement of the SIS differs from theory by 16 standard deviations.
In order to resolve this significant discrepancy, we are constructing a new experiment at the National Institute of Standards and Technology (NIST). As in all recent experiments, we will observe the lithium D lines by crossing a highly collimated lithium beam with a stable tunable laser. This will eliminate an interference between the ^{6}Li D_1 line and a ^{7}Li crossover resonance that was a major weakness of earlier saturated absorption work at NIST.[3] Unlike any of the other experiments, however, we will determine the relative positions of all lithium resonances by direct frequency metrology. A diode laser stabilized to the I_2 B-X transition R78(4-6) will serve as a local frequency reference. A second diode laser will be used to record the Doppler-free lithium resonances by laser induced fluorescence. The beat note between the spectroscopy and reference lasers will be recorded simultaneously with the spectrum to provide a precise frequency calibration for every data point in the scan. Our results should provide a definitive test of the calculated SIS. Ultimately we plan to place all of our data on an absolute frequency scale by measuring the frequency of the reference laser with a femtosecond frequency comb recently brought online in the Atomic Spectroscopy Group at NIST. This will provide additional stringent tests of QED contributions to electron binding energies in three-electron systems.

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Measurement of Femtosecond Laser Comb Frequency Offset Using Fabry-Perot Interferometer

D. Basnak[2], A. Lugovoy[1], P. Pokasov[1], S. Chepurov[1], A. Dmitriev[1,2]

[1]*Institute of Laser Physics SB RAS, Lavrentyev Avenue 13/3, Novosibirsk 630090, Russia*
[2]*Novosibirsk State Technical University, K. Marx Avenue 20, Novosibirsk 630092, Russia*

The method for measurement of comb frequency offset of femtosecond laser with narrow spectral radiation line is suggested and demonstrated. The Fabry-Perot interferometer was used as detector. The self-mode locked Cr:forsterite laser was used in our experiments.
A great progress in the field of measuring optical frequencies has been achieved due to the use of femtosecond lasers. When the radiation spectrum of this laser broadened over an octave it is possible to measure the general offset $\underline{f}_0$ of frequency comb with proper accuracy[1 2]. The way of measurement of $\underline{f}_0$ with the help of Fabry-Perot interferometer in the case, when the radiation spectrum width is essentially less than octave, is offered and realized in the present work.
The self-mode locked Cr:forsterite laser with the cavity length $\underline{L}$=1.5m was used in our experiments. The Fabry-Perot interferometer base $\underline{l}$ was equal to $\underline{L}$/2. In order to define the general offset $\underline{f}_0$ of frequency comb, the interferometer transmission was recorded by scanning interferometer length within the limits of several wavelengths λ_0. The average wavelength of a laser radiation λ_0, laser radiation spectrum width $\delta\lambda$ and frequency comb shift $\underline{f}_0$ was defined by least-square fitting of the rated dependence of interferometer transmission factor to an experimental curve. The homogeneous[3] or Gaussian shapes of the laser radiation spectrum were used for calculation procedure. For relation $\underline{l}/\underline{L}$=1/2 the interval between interferometer neighbor transmission bands is quarter of wavelength λ_0[4]. The similar coincidence is observed for both fitting procedure. The comb shift $\underline{f}_0$ is proportional to the offset of maximum of transmission band relative to the maximum of envelope. The frequency relation $\underline{f}_0/\underline{f}_{rep}$ drift of $2{\cdot}10^{-3}$ s^{-1} is observed. The differences between values obtained for homogeneous and Gaussian shapes of the laser radiation spectrum are less in comparison with the experimental accuracy.
Fabry-Perot interferometer can be used for measurement of comb frequency offset $\underline{f}_0$. The measurements accuracy could be significantly improved due to the increasing of interferometer mirror reflectivity.

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Nuclear Spin Dependent Parity Non-Conservation in Diatomic Molecules

D. Murphree[1], S. B. Cahn[1], D. Rahmlow[1], D. DeMille[1], R. Paolino[2], E. Deveney[3]

[1]*Department of Physics, Yale University*
[2]*United States Coast Guard Academy*
[3]*Bridgewater State College*

Nuclear spin-dependent parity nonconservation (NSD-PNC) effects arise from couplings of the Z_0 boson (parameterized by the electroweak coupling constants $C_{2P,N}$) and from the interaction of electrons with the nuclear anapole moment, a parity-odd magnetic moment. The effects of the anapole moment scale with the nucleon number *A* of the nucleus as $A^{2/3}$, while the Z_0 coupling is independent of *A*; the former will be the dominant source of NSD-PNC in nuclei with $A > 20$. To date, the most precise result on NSD-PNC comes from a measurement of the hyperfine dependence of atomic PNC in ^{133}Cs. However, the effects of NSD-PNC can be dramatically enhanced in diatomic molecules. We outline an experimental program to take advantage of this enhancement. We have identified over ten suitable molecules; from measurements on the nuclei in these molecules we can extract the relative contributions of the anapole moment and the electroweak Z_0 couplings. This will increase the available data on nuclear anapole moments, as well as reduce the uncertainties in current measurements of C_{2N} and C_{2P}. We report on the design of our pulsed molecular beam experiment and the current status of our efforts.

A New Search for a Spin-Gravity Interaction

D. F. Jackson Kimball, E. J. Bahr, L. R. Jacome, H. Y. Chan

Department of Physics, California State University - East Bay, Hayward, CA 94542-3084, USA

We have initiated an experiment to search for a new long-range coupling between nuclear spins and the mass of the Earth. If interpreted as a limit on a spin-gravity interaction of the form $\mathbf{S} \cdot \mathbf{g}$ between nuclear spins $\mathbf{S}$ and the gravitational field of the Earth $\mathbf{g}$, the experiment has the potential to improve present experimental limits[1] by over two orders of magnitude. Detection of a spin-gravity interaction would be evidence that gravity violated parity (P) and time-reversal (T) symmetries to a small degree, as well as being a breakdown of the equivalence principle which underlies the theory of general relativity. The experiment would also set new experimental limits on hypothetical scalar and vector components of gravitational fields, and new limits on the existence of certain classes of massless or nearly massless pseudoscalar and vector particles[2].
The experimental signature of a spin-gravity interaction is a gravity-induced energy splitting ΔE for spins oriented parallel and anti-parallel to $\mathbf{g}$:

$$\Delta E = 2k\frac{\hbar g}{c} \approx k \times 4 \times 10^{-23}\ \mathrm{eV}\ ,$$

where k is a dimensionless constant characterizing the strength of the interaction. A spin-gravity interaction also results in a torque, leading to spin precession about the axis of the local gravitational field with a frequency $\Omega_g = 2kg/c \approx k \times 2\pi \times 10^{-8}$ Hz.
This new experimental search is motivated by recently developed techniques in the field of atomic magnetometry[3,4]. The experiment will use nonlinear optical rotation of near-resonant laser light to measure the spin-precession frequency of rubidium atoms in the presence of a magnetic field $\mathbf{B}$, and we anticipate achieving a sensitivity of $1\ \mu\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ to Rb spin precession. The difference between the precession frequencies for the two different ground state hyperfine levels of Rb, which have nearly equal and opposite gyromagnetic ratios, would yield a signal proportional only to anomalous interactions that do not scale with the magnetic moments. The sum of the precession frequencies enables an ultra-precise determination of $\mathbf{B}$ to correct for associated systematic errors. (By simultaneously measuring spin-precession in both ground-state hyperfine levels the valence electron spin serves as a co-magnetometer for the nuclear spin.)
We report on a systematic optimization of sensitivity to Rb spin precession and investigation of a variety of possible systematic errors. Our research is supported by the National Science Foundation under grant PHY-0652824.

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The YbF electron electric dipole moment measurement: Data aquisition and analysis.

D. M. Kara, J. J. Hudson, B. E. Sauer, M. R. Tarbutt, E. A. Hinds

Centre for Cold Matter, Blackett Laboratory, Imperial College London, London, SW7 2AZ, United Kingdom

A non-zero electric dipole moment (EDM) of a fundamental particle violates time reversal (T) symmetry [1]. The standard model does accomodate T violation, but for the electron EDM it predicts a value far smaller than the current experimental limit. However, many modern extensions of particle theory lead quite naturally to a value in the range of 10^{-27}e.cm or a little below[2]. Our experiment using cold YbF molecules aims to be more sensitive than this. It is a search for physics beyond the standard model. It is difficult to formulate a particle physics theory which violates the combined symmetry CPT, therefore an electron EDM near the current level would also imply a new type of CP violation, beyond the usual CKM mechanism.
It has long been recognized that heavy polar molecules are extremely sensitive systems in which to measure T violation. At Imperial College London we have built and are running a molecular beam experiment using YbF to make this measurement. This apparatus has been extensively modified from its previous configuration[3]. A particular improvement has been the use of the high voltage electric field plates as a radiofrequency transmission line. The machine has also been highly automated. During data collection nine experimental parameters are modulated. The demodulated signal channels allow us both to control systematic effects which might mimic an electron EDM and also to optimise the machine for maximum sensitivity. We will describe the data aquisition and analysis techniques. We will discuss the sensivity of our current data set, with particular emphasis on technical and intrinsic noise limitations.

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Antihydrogen Production in a Penning-Ioffe Trap

D. Le Sage[1], W. S. Kolthammer[1], P. Richerme[1], P. Larochelle[1], B. Levitt[1], R. McConnell[1], J. Wrubel[1], G. Gabrielse[1], A. Speck[2], M. C. George[3,4], A. Carew[3], D. Comeau[3], M. Weel[3], E. A. Hessels[3], C. H. Storry[3], D. Grzonka[4], Z. Zhang[4], W. Oelert[4], J. Walz[5]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2]*Rowland Institute at Harvard, Harvard University, Cambridge, Ma 02142, USA*
[3]*York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*
[4]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[5]*Institut fur Physik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*

The long-term goal of the ATRAP collaboration is to perform precise laser spectroscopy of antihydrogen, the simplest atom made entirely of antimatter, in order to compare the spectra of antihydrogen and hydrogen as a test of CPT invariance. To make a precise measurement using the small number of antihydrogen atoms that are typically produced, it will first be necessary to magnetically confine the atoms. To this end, a new apparatus was recently constructed that incorporates a Penning trap for the confinement and mixing of antiprotons and positrons to form slow antihydrogen atoms, along with a superimposed quadrupole Ioffe trap to confine the atoms produced. Sufficient numbers of particles remain confined in the Penning trap to produce antihydrogen, despite the loss of cylindrical symmetry caused by the radial field of the Ioffe trap[1]. Antihydrogen production within the Ioffe trap has also been demonstrated recently, although trapped atoms have not yet been detected[2]. A number of modifications to the experiment are presently in development to improve upon this recent progress.

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Possible Constraints on Time-Dependence in the Speed of Light from Lunar Laser Ranging

Felix T. Smith

Molecular Physics Laboratory, SRI International, Menlo Park, CA, USA

By using lunar laser ranging (LLR) data it is proposed to measure experimental constraints on the time dependence of the velocity of light (or, with the present defined value for c, the time dependence of the effective length scale). LLR measurements of lunar distance since 1994 have been accurate to a few parts in 10^{10} [1]. The newly activated APOLLO project at Apache Point is improving sensitivity further by a factor of 10 or 20 [2], [3]. The lunar recession rate is 3.8 cm/yr [4], a change of one part in 10^{10} per year in the lunar distance. The quality of the expected data will now allow dc/dt to be measured as an additional parameter independent of the recession rate, and should allow establishment of an upper bound on $\dot{c}/c$ about an order of magnitude smaller.

It is usually believed that c is an invariant in special relativity, but there is no experimental evidence to confirm this at the level of a time constant as long as that of the Hubble expansion, $a_0 = 1.37 \times 10^{10}$ yr. The LLR data since 1994 may already be precise enough to establish such a limit. Observed signal times yield distance estimates ρ between surface sites on earth and moon. Orbital predictions give center-to-center distances r. The difference $\rho - r$ is a projection of the time-independent radius vectors of earth and moon. A statistical treatment then allows the radii of earth and moon to be used as standard lengths to estimate $\dot{c}/c$. This will allow $\dot{c}/c$ to join such issues as $\dot{G}/G$, the strong equivalence principle, and possible new interactions beyond the Standard Model, on which LLR can provide meaningful experimental limits.

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Towards a Beta Asymmetry Measurement of Polarized Radioactive Atoms in an Optical Dipole Trap

F. Fang, H. Wang, D. Feldbaum, D. J. Vieira, X. Zhao

Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Laser cooled and trapped radioactive atoms provide an ideal sample for studying parity violation in beta decay. We present recent progress in undertaking a high precision beta-recoil measurement of radioactive ^{82}Rb atoms in an optical tweezer. We have demonstrated the loading of ^{82}Rb atoms from a magneto-optical trap (MOT) to a far off resonance dipole trap formed by a YAG laser and observed the evidence of spontaneous spin polarization of atoms in optical dipole trap loading. We'll present the latest progress in polarizing the sample with optical pumping and precision measurement of the sample polarization. In our proposed beta asymmetry measurement, we plan to load ^{82}Rb atoms from a MOT into an optical tweezer and then beam the atoms down to a science chamber where the atoms will be polarized and their beta decay will be measured.

An Atom Interferometer for Gradient Magnetometry

J. P. Davis, F. A. Narducci

Naval Air Systems Command, EO Sensors Division, Patuxent River, MD 20670, USA

Precision measurements of rotation, gravity, gravity gradients and time are often performed using atom interferometers[1]. It has long been known that mass scaling can potentially increase the sensitivity of atom interferometers over an otherwise equal optical interferometer by an amazing 11 orders of magnitude [2]. However, magnetic fields and magnetic field gradients are not among the list of fields whose state of the art depends on atom interferometers. Under our usual conditions of interest which involve a magnetometer on a moving platform (typically, an aircraft), very small signals of interest can be masked by local and environmental noise.

Atom interferometers are insensitive to actual magnetic field strength to first order but are sensitive to magnetic field gradients. We have shown [3] that in a standard configuration, the phase of the interferometer readout is given by

$$\Delta\phi = -k_{eff}\left(g + \frac{\mu}{m}\frac{dB}{dz}\right)T^2 \tag{2}$$

where k_{eff} is the wave-number associated with the laser(s) producing the optical fields that create the atomic superposition used in the interferometer, g is gravity, μ is the Bohr magneton, m is the mass of the atom being used and T is the time in-between laser pulses. In utilizing atom interferometers for our application, the challenge has moved from the detection of weak magnetic fields in a noisy environment to the detection of small magnetic field gradients against the effects of gravity. However, by employing the techniques of "interferometer reversal", effects of gravity can be cancelled out.

We have experimentally demonstrated the methods we use to detect states of different mF number and show how to create a superposition of such states. We avoid the usual requirement of two phase locked lasers by using magnetic sublevels of the same hyperfine state and a single laser field to drive the Raman transitions. Finally, we have considered the limits of sensitivity of such a device. By using realistic numbers [4], we can show that the minimum detectable gradient magnetic field is on the order of $0.1pT/\sqrt{Hz}$. This number, while perhaps not extremely competitive with current magnetometers, is based on a very short baseline (15mm). Because this device is directly sensitive to gradient magnetic fields and therefore, by definition, all components are common to the system, we expect to see excellent "common-mode" noise rejection.

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Using Feshbach resonance to observe variation of fundamental constants in ultracold atomic and molecular gases

M. Gacesa, R. Côté

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

It has been shown that the scattering length can be very sensitive to the variation of the electron-to-proton mass ratio[1], or $m_e/m_p = m_e/\Lambda_{QCD}$, where Λ_{QCD} is the standard QCD scale. Using full coupled-channel approach, we compute the enhancement near a Feshbach resonance for several alkali systems that have been experimentally realized. Since photoassociation rate (PA) for production of ultracold molecules is very sensitive to the change of the scattering length, we calculate the influence of electron-to-proton mass ratio on the PA formation rate of ground state alkali molecules. Based on the current limits[2], sensitivity of 1% in the measurement of PA rate might be sufficient to detect the variation of mass ratios.

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Bloch oscillations in an optical lattice: a tool for high precision measurements

M. Cadoret[1], E. de Mirandes[1], P. Cladé[1], S. Guellati-Khélifa[2], C. Schwob[1], F. Nez[1], L. Julien[1], F. Biraben[1]

[1]*Laboratoire Kastler Brossel, UPMC, Ecole Normale Supérieure, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France*
[2]*INM, Conservatoire National des Arts et Métiers, 292 rue Saint Martin, 75141 Paris Cedex 03, France*

Bloch oscillations of ultracold atoms in an optical lattice, turn out to be a promising technique for high precision measurements in atomic physics. This method allows us to transfer efficiently a large number of photon momenta to the atoms. It is applied to measure the recoil velocity[1] or the local acceleration of gravity [2].
We report two different experimental schemes based on this phenomena : the first one is devoted to the measurement of the ratio h/m between the Planck constant and atomic mass. This measurement leads to the determination of the fine structure constant α. For this purpose, we use a Bloch oscillations (BO) in accelerated lattice. We have realized two determinations of α by combining BO either with a non-interferometric velocity sensor ($\pi - \pi$) or an interferometric sensor $(\pi/2 - \pi/2 - \pi/2 - \pi/2)$ (see F. Biraben talk).
The second scheme is implemented by using BO in vertical standing wave. In this case the measurement of the oscillation period leads to the determination of the local acceleration of gravity g.
We are also investigating the possibility to perform a large momentum beam splitter based on BO, in order to improve substantially the sensitivity of atomic interferometer.
All this approaches will be deeply discussed in this poster.

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Single-Proton Self-Excited Oscillator

N. Guise, J. DiSciacca, G. Gabrielse

Department of Physics, Harvard University, Cambridge, MA 02138, USA

A new apparatus and experiment adapts techniques from the recent electron g-2 measurement[1] to a single proton suspended within a Penning trap. Our primary goal is a direct observation of the single-proton spin-flip transition, which would open the way to a novel measurement of the proton magnetic moment, and allow a comparison of the proton and antiproton g-factors at precision likely to be a million times higher than achieved to date. Central to our proposal is the use of a self-excited oscillator for this measurement in order to realize the extremely high frequency sensitivity that is required[2]. (There is a related proposal from Mainz-GSI-Heidelberg without the use of the self-excited oscillator[3,4].)

As in the electron experiment, the spin state is coupled to the axial motion via a magnetic bottle coupling method[5], such that a small shift in axial frequency will indicate the spin-flip transition. However, the large proton mass presents significant experimental challenges compared to the equivalent single-electron system. In particular, the size of the magnetic moment and the signal/noise available for axial detection are both reduced by a factor of order $\frac{\mu_N}{\mu_B}$, the ratio of a nuclear and a Bohr magneton. To partially compensate, our proton Penning trap is designed with a magnetic bottle roughly 50 times stronger than was used for the electron.

We have successfully trapped a single proton in this relatively inhomogeneous magnetic field, but observing the spin-flip transition will require substantial improvement in resolution of the axial frequency. As an initial milestone, we have achieved the first single-proton self-excited oscillator. This feedback scheme, earlier demonstrated with an electron[2], allows for a large-amplitude oscillation despite the inherent anharmonicity of our Penning trap, and promises stability approaching the level required for spin-flip detection.

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Nanoscale magnetic sensing with an individual electronic spin in diamond

J. R. Maze[1], J. S. Hodges[1,3], P. L. Stanwix[2], S. Hong[1], J. M. Taylor[4], P. Cappellaro[1,2], L. Jiang[1], A. S. Zibrov[1], E. Togan[1], M. V. G. Dutt[1], A. Yacoby[1], R. Walsworth[1,2], M. D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138 USA*
[2]*Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138 USA*
[3]*Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA*
[4]*Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02138 USA*

The ability to sense nanotelsa magnetic fields with nanoscale spatial resolution is an outstanding technical challenge relevant to the physical and biological sciences. For example, detection of such weak localized fields will enable sensing of magnetic resonance signals from individual electron or nuclear spins in complex biological molecules and the readout of classical or quantum bits of information encoded in an electron or nuclear spin memory. Here we present a novel approach to nanoscale magnetic sensing based on coherent control of an individual electronic spin contained in the Nitrogen-Vacancy (NV) center in diamond. At room temperature, using an ultra-pure diamond sample, we achieve shot-noise-limited detection of 3 nanotesla magnetic fields oscillating at kHz frequencies after 100 seconds of signal averaging. Furthermore, we experimentally demonstrate nanoscale resolution using a diamond nanocrystal of 30 nm diameter for which we achieve a sensitivity of 0.5 microtesla / $Hz^{1/2}$.

The YbF electron electric dipole moment measurement: diagnostics and systematics

J. J. Hudson, B. E. Sauer, D. M. Kara, M. R. Tarbutt, E. A. Hinds

Centre for Cold Matter, The Blackett Laboratory,
Imperial College London, London SW7 2AZ, United Kingdom

We present recent work on our measurement of the electron's electron dipole moment (e-edm). The e-edm is a hypothesised, tiny distortion of the electron's charge[1]. It comes about through the interactions of heavy particles in the polarised vacuum-field surrounding the electron. It can be thought of as a probe of these interactions, and is a surprisingly powerful one at that: a measurement of the e-edm would heavily constrain any possible extensions to the Standard Model of particle physics. A non-zero result would be unambiguous evidence for physics beyond the Standard Model[2].
The current upper bound on the edm lies at 1.6×10^{-27}e.cm (about 10^{-18} Debye)[3]. We are seeking to improve upon that measurement. We have for some time been recording datasets with a statistical precision better than the current world limit. A complete measurement, though, is much more than this, requiring careful consideration of any spurious effect that could mimic an e-edm signal. We have been developing techniques for diagnosing the condition of our experimental apparatus and mapping the fields within it[4], which we will present. We have also been modelling the physics of the experiment in great detail, with an emphasis on possible systematic errors: we will present some of the highlights.

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Progress on a New Search for the Permanent Electric Dipole Moment (EDM) of ^{199}Hg

T. H. Loftus[1], E. N. Fortson[1], W. C. Griffith[2], B. R. Heckel[1], M. V. Romalis[3], M. D. Swallows[4]

[1]*Department of Physics, University of Washington, Seattle, WA 98195, USA*
[2]*National Institute of Standards and Technology, Boulder, CO 80309, USA*
[3]*Department of Physics, Princeton University, Princeton NJ 08544, USA*
[4]*JILA and the University of Colorado, Boulder, CO 80309, USA*

Observation of a nonzero EDM would imply CP violation beyond the Standard Model. The most precise EDM limit, established by our group several years ago for ^{199}Hg, is $|d_{Hg}| < 2.1\times10^{-28}$ *e* cm[1]. To further refine these measurements, we switched from two to four spin-polarized Hg vapor cells: two lie in parallel magnetic and anti-parallel electric fields, resulting in EDM-sensitive spin precession; the remaining two cells, at zero electric field, serve to cancel noise generated by magnetic field gradients and limit systematics due to charging and leakage currents. To prevent experimenter bias from influencing the data, we have also instituted a blind analysis protocol whereby a randomly generated, hidden, and EDM-mimicking frequency shift (within the range allowed by Ref. [1]) is applied to the EDM-sensitive frequency channels. To date, the statistical uncertainty for the new EDM data is of order 1×10^{-29} *e* cm, a $> 4\times$ improvement over our previous measurement.
Constraining systematics at a similar level requires understanding and mitigating Stark interference, an EDM-mimicking vector light shift that is linear in the electric field and probe beam intensity[2]. To this end, we have explored: (1) comparing precession data at two probe wavelengths where the Stark interference light shifts are equal but opposite, (2) eliminating Stark interference by determining the Larmor frequency “in the dark” between two probe pulses that establish the Larmor phase at the beginning and end of the dark period, and finally (3) determining the Stark interference amplitude via measurements of the Larmor precession for parameter settings that maximize the corresponding frequency shift. In the latter case, we use a range of probe beam intensities and vector configurations for the electric and magnetic fields and the probe beam polarization as additional checks on the qualitative behavior of the data and the extracted interference amplitudes. Each night of data involves several hundred high voltage reversals. From 82 nights of data spanning four vector configurations and a factor of six in the probe beam intensity, we obtain a preliminary value for the interference amplitude of $(a_{M1} + a_{E2})$ = $(0.39 \pm 0.39_{stat})\times10^{-8}$ (kV/cm)$^{-1}$. This value implies that Stark interference systematics can be controlled to $<1\times10^{-29}$ *e* cm for our typically employed experimental settings.
In addition to these results, we will discuss sensitivity limits for the experiment, remaining systematic effects, and our overall progress on this improved measurement of the ^{199}Hg EDM.

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Search for an electron EDM with molecular ions

H. Loh[1], R. Stutz[1], L. Sinclair[1], H. Looser[2], E. A. Cornell[1]

[1] *JILA/University of Colorado, Boulder, CO 80309, USA*
[2] *Department of Physics, University of Applied Sciences, Northwestern Switzerland, Windisch, Switzerland*

The $^3\Delta_1$ state of HfF^+ has been proposed as a candidate for the search for an electron electric dipole moment (EDM). Laser ablation of a Hf target in the presence of Ne + 1%SF_6 creates HfF molecules, which are cooled to rotational temperatures of $\sim 10K$ in a supersonic expansion. We report recent experimental work on photoionization of these neutral HfF molecules to generate HfF^+.

A mobile atom interferometer for high precision measurements of local gravity

M. Schmidt, A. Senger, T. Gorkhover, U. Eismann, S. Grede, E. Dischke, E. Kovalchuk, A. Peters

Humboldt Universität zu Berlin, AG Quantenoptik und Metrologie, Hausvogteiplatz 5-7, 10117 Berlin, Germany

In recent years, matter wave interferometry has developed into a powerful tool for the ultra precise measurement of accelerations and rotations. It is used in various laboratories for experiments in the fields of fundamental physics and metrology.

We present a new design for a gravimeter based on atom interferometry which is optimized for mobility and mechanical stability. This setup will open up the possibility to perform on-site high precision measurements of local gravity. We report on the status of the project and its subsystems including a rack-mounted cooling and raman laser system.

This gravimeter is developed within the FINAQS project, a collaboration of five European research groups that aims at developing new atomic quantum sensors.

Electric Dipole Moments as Alternative Probes for Finding New Physics Beyond Standard Model

H. S. Nataraj[1], B. K. Sahoo[2], B. P. Das[1], D. Mukherjee[3]

[1]*Indian Institute of Astrophysics, Bangalore - 560034, India*
[2]*KVI, University of Groningen, NL-9747 AA Groningen, Netherlands*
[3]*Raman Center of Atomic, Molecular and Optical Sciences, IACS, Kolkata - 700032, India*

The non-zero electric dipole moment (EDM) of any non-degenerate physical system will provide an unambigious signature of Parity and Time reversal violations in Nature. The open-shell atoms will have two dominant sources of intrinsic electric dipole moments (EDMs); one due to the intrinsic EDM of the constituent electrons and the other due to the parity and time-reversal violating scalar–pseudo-scalar (S-PS) interactions between the electrons and the nucleus. Both these couplings are so meager that they are generally neglected while determining atomic properties. The electron EDM and and S-PS EDM contribution to atomic EDM scales as the cube of the atomic number and hence the heavy paramagnetic atoms will exhibit large EDMs. However, despite the relentless experimental search for EDMs in elementary particles and as well as in the composite systems such as atoms, molecules and other solid-state systems for more than over five decades has not yielded any conclusive result so far. Thus it is quite intriguing and pose a challenge to the high precision atomic experimentalists. Many state-of-art atomic EDM experiments are currently being pursued in different laboratories with the aim of achieving better detection limits, a few orders of magnitude lower than the current experimental limits.

Though, the intrinsic EDM of the electron is of great fundamental interest, one measures the EDM of the composite systems like paramagnetic atoms because of their enhanced EDM and also because of the ease in treating the neutral systems when compared to ions in externally applied strong electro-magnetic fields. Further, one deduces the limit for electron EDM by combining the theoretical enhancement factors and the measured atomic EDMs. Thus, one needs high precision in both theory and measurement in obtaining a better limit on electron EDM. We have performed a rigorous atomic many-body calculation using the relativistic coupled-cluster (RCC) method and predicted the EDM enhancement factors for Rubidium and Cesium with a sub 1% accuracy [1]. Our results of enhancement factors when combined with the measurements of the EDMs of these atoms when they reach the desired level of accuracy could unfold a novel direction for new physics beyond the much celebrated model of particle physics till date, the Standard Model, which indeed is quite significant as an additional probe for finding new physics in the era of the Large Hadron Collider (LHC). Here, we describe the RCC method applied in obtaining the precise EDM enhancement factors for Rb and Cs and discuss the results and its implications on particle physics and cosmology.

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Measurement of the Rb D2 Transition Linewidth at Ultralow Temperature

G. A. Noble, B. E. Schultz, H. Ming, W. A. van Wijngaarden

Department of Physics and Astronomy, York University, Toronto, Canada

The Rb D2 linewidth was studied using atoms cooled to a temperature of 50 μK that were contained in a magneto-optical trap. The transmission of a probe laser through the atom cloud was monitored using a CCD detector. The frequency of the probe laser was scanned across the resonance using an acousto-optic modulator. The observed lineshape was very well fitted by a Lorentzian function. The full width half maximum linewidth was examined as a function of the optical depth and the probe laser intensity. The extrapolated value at zero optical depth 6.062 $\pm$ 0.017 MHz corresponds to a $5P_{3/2}$ lifetime of 26.25 $\pm$ 0.07 nsec. This result agrees with lifetimes found in experiments that measured the temporal decay of fluorescence or photoassociation spectroscopy and is somewhat below the result of a relativistic many body perturbation calculation.

A cold atom gravimeter for onboard applications

N. Zahzam, O. Carraz, Y. Bidel, A. Bresson

ONERA, Departement de Mesures PHysiques, 91 761 Palaiseau, France

Atom interferometry is now proven to be a very efficient technique to achieve highly sensitive and absolute inertial sensors. As a matter of fact accelerometers such as gyroscopes [1] or gravimeters [2] based on this technique by using cold atoms have already been developped. However state of the art laser cooling techniques are too sensitive to environmental disturbances to ensure onboard applications with such instruments.

We are presently developping a Rb^{85} cold atom gravimeter based on a compact and reliable laser system operational in onboard conditions. The optical system relies on the frequency doubling of a telecom fiber bench at 1560 nm [3]. The starting point of the gravimeter is a vapour loaded MOT of $\approx 10^8$ atoms. The atoms are then released and during the fall a sequence of three Raman pulses forms a Mach-Zehnder type interferometer. The interferometer's phase, which depends on the gravity acceleration, is finally read by means of a fluoresence detection measuring the population of the two atomic states involved in the raman transitions.

Besides last results we obtain on gravity acceleration measure, we will present the details of the experiment setup and particularly the optical part which partly garantees the onboard character of the gravimeter. The laser system is indeed composed of a fibered laser (master laser) frequency doubled in a Periodically Poled Lithium Niobate (PPLN) wave guide crystal and locked via saturated absorption. A second laser (slave laser) is frequency locked on the master laser at an arbitrary frequency difference with a beatnote lock. Moreover sidebands are generated by modulating the slave laser with a fibered phase modulator. This phase modulation technique allows us to generate the two optical frequencies needed during the cooling stage (cooling laser and repumping laser) and the interferometer sequence (Raman lasers) by using a unique laser diode. The 1560 nm laser system is then amplified in a 5 W Erbium Doped Fiber Amplifier and frequency doubled in a double pass configuration using a PPLN crystal. Such a system allows us to obtain $\approx$ 0.8 W at 780 nm. This laser setup has already been tested successfully under micro ($\approx$ 0g) and hyper ($\approx$ 2g) gravity inside the CNES ZERO-G Airbus plane in the frame of the ICE (*Interférométrie Cohérente pour l'Espace*) project [4].

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Precision spectroscopy of ^{3}He at 1083 nm

P. Cancio[1,2], L. Consolino[2], G. Giusfredi[1,2], P. De Natale[1,2], M. Inguscio[2]

[1]*CNR-Istituto Nazionale di Ottica Applicata, Firenze, Italy*
[2]*LENS and Dipartimento di Fisica, Universitá di Firenze, Sesto Fiorentino, Italy*

Since the introduction of Optical Frequency Combs (OFC) as a tool for precision spectroscopy of optical-near infrared atomic transitions, the accuracy of frequency measurements has been improved several orders of magnitude. In particular we already improved the accuracy of $2^3S_1 \rightarrow 2^3P_{0,1,2}$ frequencies in ^{4}He by 30 times using an OFC[1]. In this conference we extend for the first time this kind of measurements to the ^{3}He isotope. The experiment has been upgraded with respect to the one described in [1] by phase-locking to the OFC two 1083 nm diode sources resonant with different He transitions. In this way, absolute frequency of the 1083 nm transitions and frequency difference between them are simultaneously performed, cancelling some time-dependent systematic effects in the relative measurements. These measurements can be used to test the QED theory of the simplest bounded three-body system. Moreover, the relative frequencies give directly the hyperfine structure (HFS) of the ^{3}He 2^3P level, with an accuracy improved by at least one order of magnitude with respect to the previous values published more than twenty years ago[2]. The three ^{3}He hyperfine interaction constants can be improved with these measurements and the strong hyperfine contribution to the 2^3P energies can be experimentally determined in order to get the ^{3}He-^{4}He isotope shift (IS) measurements of the transition. Accurate information about the different nuclear volume of the two isotopes can be determined by comparison between IS measurements and theoretical determinations. Moreover, the extracted FS ^{3}He 2^3P energies, corrected for the hyperfine interaction, can be used to test the mass dependent QED terms of the already developed theory for ^{4}He. It can help to understand the discrepancies between theory and experiment for the FS ^{4}He 2^3P energies, which is actually the limit to get a fine structure constant determination from He FS[3].

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Recent Results from the PbO* Electron EDM Experiment

P. Hamilton[1], S. Bickman[2], Y. Jiang[1], H. Smith[1], D. DeMille[1]

[1]*Department of Physics, Yale University, New Haven, CT 06520, USA*
[2]*National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA*

A CP-violating permanent electric dipole moment (EDM) of the electron, d$_e$, is of considerable interest in elementary particle physics. Many favored extensions of the Standard Model (including most supersymmetric models) predict $|d_e|$ within 3 orders of magnitude of the current experimental limit[1], $|d_e| < 1.6 \times 10^{-27} e \cdot cm$. Since the standard model prediction[2] for d_e is exceedingly small, a 100-fold or greater improvement in sensitivity could exclude many high energy models or provide evidence for new physics.
This experiment uses the metastable $a(1)[^3\Sigma^+]$ state of the PbO molecule. Several unique properties of this state, including closely spaced levels of opposite parity and a long coherence time, make it suitable for use in a vapor cell, which in turn enables high counting rates. The closely spaced levels of opposite parity are due to Ω-doubling. Roughly speaking this doubling leads to states with oppositely directed internal electric fields but otherwise nearly identical properties. This reversal along with those of the lab electric and magnetic fields allow us to greatly reduce most systematics. We report a shot-noise limited result of $d_e = 1.9 \pm 2.0(stat) \times 10^{-26} e \cdot cm$ from the first data taking run. We also discuss a preliminary investigation of the limits we can place on several sources of systematic error including imperfect electric and magnetic field reversals. We anticipate in increase in sensitivity of 10-100 in the near future with a new detection scheme currently being implemented.

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Precise measurements of hyperfine structure and atomic polarizability in indium and thallium

P. K. Majumder, P. W. Hess, M. Gunawardena

Department of Physics, Williams College, Williamstown, MA 01267

We are pursuing a series of precise atomic structure measurements in atomic thallium and indium designed to test new ab initio theory calculations in these three-valence-electron systems[1]. For thallium, independent atomic theory calculations are essential for atomic physics-based tests of Parity nonconservation and future tests of Time-reversal violation in this system. In our indium experiment (see figure), using two-color laser excitation, the hyperfine constants of the $6P_{3/2}$ excited state of indium(I=9/2) have been measured for the first time. We excite ground-state atoms to the $6S_{1/2}$ state using a 410 nm external cavity diode laser which is locked to this indium transition using a new technique involving differential vapor cell transmission measurements from a pair of AOM-shifted laser beams. A second laser beam at 1291 nm overlaps the blue beam in a heated indium vapor cell, driving Doppler-narrowed hyperfine transitions to the $6P_{3/2}$ excited state. By modulating the blue laser beam and using lock-in detection, we obtain background-free, low-noise IR hyperfine spectra. Current statistical precision is at the MHz level, and preliminary results agree well with recent theory predictions for the hyperfine constants.

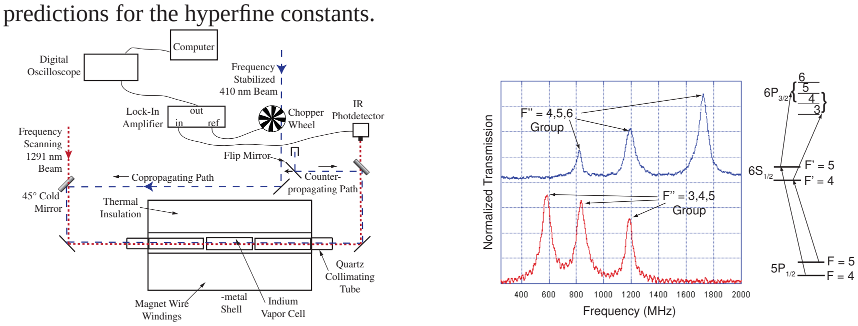

Figure 1: *Sketch of indium spectroscopy setup (left). Hyperfine scans and levels (right).*

In a second experiment, we are making use of our existing high-flux atomic beam apparatus to perform an analogous two-step diode laser excitation experiment in thallium. Previously, using this apparatus, we completed a 0.5% measurement of the polarizability in the thallium $6P_{1/2}$ - $7S_{1/2}$ 378 nm transition using a frequency-doubled diode laser system. Our result is in excellent agreement with a new ab initio calculation of thallium atomic structure[2]. We have recently obtained a GaN diode laser system at 378 nm, and with this new tool, we intend to pursue a two-step excitation experiment by overlapping the UV laser and a second IR laser (tuned to the 1301 nm $7S_{1/2}$ - $7P_{1/2}$ transition) in our atomic beam apparatus. A precise measurement of the polarizability of this second-step transition will then be completed.

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Seeking More Accurate Measurements of the Electron and Positron Magnetic Moments

S. Fogwell, D. Hanneke, G. Gabrielse

Department of Physics, Harvard University, Cambridge, MA 02138, USA

A new measurement using a one-electron quantum cyclotron gives an improved value for the electron magnetic moment, $g/2 = 1.001\,159\,652\,180\,(73)\;[0.28\;\mathrm{ppt}]$[1], whose uncertainty is 2.7 and 15 times smaller than previous measurements in 2006[2] and 1987[3]. When combined with a quantum electrodynamics (QED) calculation, the new measurement determines the fine structure constant, α, to the 0.37 ppb level[1], a factor of 1.9 improvement over the 2006 result[4], and twenty times more accurate than atom-recoil determinations[5,6]. Comparisons of these independent measurements of α provide the most stringent test of QED theory.

The new measurement uses many of the same techniques as the 2006 measurement with some additional improvements. Our single-electron quantum cyclotron[7] is held in a cylindrical Penning trap[8] to inhibit spontaneous emission. The low temperature (100 mK) narrows the linewidths of the measured frequencies and inhibits stimulated absorption in the cyclotron motion, effectively locking it in its ground state. A self-excited oscillator increases signal-to-noise[9]. The electron is used as its own magnetometer, allowing accumulation of quantum-jump line statistics over days. A new method using the spontaneous emission rate of a single electron gives a more accurate picture of the cavity mode structure and determines the corrections for the effects of the interaction of the electron with the cavity modes.

On-going and future work includes the installation of a new high-stability apparatus and new techniques including cavity sideband cooling which will cool the axial motion near its quantum ground state, narrowing the lines and allowing a more controlled measurement. In addition, work is underway to incorporate a positron source in the new apparatus, allowing measurements of the positron magnetic moment using the same techniques developed and used so successfully for the electron. A comparison of the positron and electron magnetic moments provides constraints on violations of lepton CPT and Lorentz invariance.

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Experiment to search for electron electric dipole moment using laser-cooled Cs atoms

Y. S. Ihn, D. J. Heinzen

Department of Physics, University of Texas at Austin, Austin, TX 78712, USA

A nonzero value of the electron electric dipole moment d_e can exist if time reversal symmetry(T) is violated.[1] The electron EDM in the standard model is predicted to be $10^{-38}\ e\cdot cm$, far too small to be detected experimentally. However, extensions of the standard model, such as low-energy supersymmetry, allow for a value of d_e that could be as large as about ten times the current experimental bound $\mid d_e \mid < 1.6 \times 10^{-27}\ e \cdot cm$.[2] The previous atomic EDM experiments were limited by the statistical uncertainty and systematic errors. Our measurement will be much more sensitive than previous measurements because atoms can be stored in the trap for tens of seconds, allowing for much narrower Zeeman resonance linewidths. Also our method will eliminate the most important systematic errors, proportional to atomic velocity, which have limited previous experiments. In this presentation, we will describe the design of our new apparatus which is designed to be sensitive to an electron EDM as small as $10^{-29}\ e\cdot cm$. An important feature of our experimental apparatus is that magnetic field noise will be suppressed to a very low value of the order of $1fT/\sqrt{Hz}$. This requires careful attention to the Johnson noise currents in the chamber, which have not been important in previous experiments. In the experimental process, we will use laser-cooled Cs atoms loaded and captured in optical molasses from a separate 2D MOT cold atom source. The atoms diffusing in the optical molasses will be trapped by two far-off resonance optical dipole force traps (FORT).[3] High voltage electrodes will apply opposite polarity electric fields to the two traps. The signature of an EDM would be a first-order electric field shift of the atomic Zeeman levels upon reversal of the electric fields.

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Long Arm With Large Separation Atom Interferometers

Tao Hong[1,2]

[1] *Harvard-MIT CUA, Dept. of Phys., Harvard University*
[2] *JQI, Dept. of Phys., University of Maryland. E-mail: taohong01@gmail.com*

We propose to realize a coherent large angle atomic beam splitter by using the magnetically induced optical clock transition between states $^1S_0$ and $^3P_0$ of an even isotope of alkaline (or rare) earth elements[1]. This type of transition allows us to uniquely divide the beam splitting process into two steps. The first step is mainly to produce a superposition of the two clock states by pulsing on a localized magnetic field and a clock laser simultaneously to produce a $\pi/2$ pulse. The second step is mainly to make a large spatial separation between the two clock states by applying a moving optical lattice and transferring a large number of transverse momentums to only one of the clock states through, for instance, Bragg deflection. This is possible due to the fact that the separation between $^1S_0$ and $^3P_0$ is in optical frequency domain and we can always set the lattice laser wavelength very close to a transition resonance connecting to one clock state and simultaneously hundreds nanometers away from all possible transition resonance connecting to the other clock state. To suppress the spontaneous scattering loss of the former state caused by the optical lattice, the laser frequency should also be sufficiently far blue detuned from the selected resonance. Or an alternative method is, analogous to the solution for optical lattice clocks, to choose a magic wavelength so that the light shift for one of the clock state is zero, but not for the other. After the first step of beam splitting into two clock states, no magnetic field causes any further decay of the $^3P_0$ state, so the interferometer arms formed by these states can be very long. As usual, we can also use a reversed process to combine two separated arms together to form interference and hence a complete interferometer. More specifically, we give an interferometer scheme for rotation measurement, in which we employ four atomic beams in order to remove some of the possible systematic errors and relax the frequency stability requirement for the clock laser, as shown in Fig. 1.

I would like to thank Steven Rolston, Norval Fortson, Yuzhu Wang and Mara Prentiss for helpful discussions.

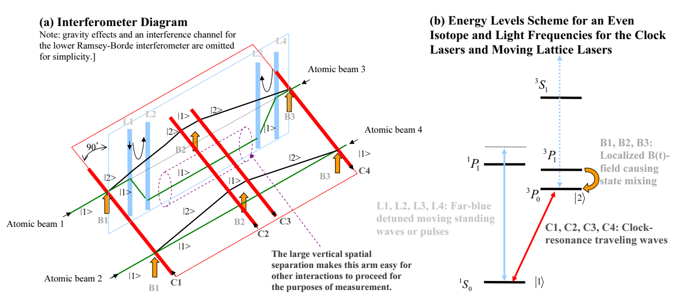

Figure 1: *(color online). An atom interferometer for rotation measurement.*

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News from the Muonic Hydrogen Lamb Shift Experiment

T. Nebel[1], F. D. Amaro[9], A. Antognini[1], F. Biraben[2], J. M. R. Cardoso[9], D. S. Covita[9], A. Dax[3,6], S. Dhawan[6], L. M. P. Fernandes[9], A. Giesen[11], T. Graf[10], T. W. Hänsch[1], P. Indelicato[2], L. Julien[2], C.-Y. Kao[8], P. E. Knowles[5], F. Kottmann[4], E.-O. Le Bigot[2], Y.-W. Liu[8], J. A. M. Lopes[9], L. Ludhova[3,5], C. M. B. Monteiro[9], N. Moschüring[1], F. Mulhauser[5,1], F. Nez[2], P. Rabinowitz[7], J. M. F. dos Santos[9], L. A. Schaller[5], K. Schuhmann[11], C. Schwob[2], D. Taqqu[3], J. F. C. A. Veloso[9], R. Pohl[1]

[1]*MPQ Garching Germany*
[2]*LKB Paris France*
[3]*PSI Villigen Switzerland*
[4]*ETH Zürich Switzerland*
[5]*Université Fribourg Switzerland*
[6]*Yale University U.S.A.*
[7]*Princeton University U.S.A.*
[8]*NTHU Hsinchu Taiwan*
[9]*Universidade de Coimbra Portugal*
[10]*IFSW Universität Stuttgart Germany*
[11]*Technologiegesellschaft für Strahlwerkzeuge mbH Stuttgart Germany*

The Lamb shift experiment in muonic hydrogen ($\mu^- p$) aims to measure the energy difference between the $2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$ atomic levels to a precision of $30\,$ppm. This would allow the proton charge radius r_p to be deduced to a precision of 10^{-3} and open a way to check bound-state QED to a level of 10^{-7}. The poor knowledge of the proton charge radius restricts tests of bound-state QED to the precision level of about 6×10^{-6}, although the experimental data itself (Lamb shift in hydrogen[1]) has reached a precision of 2×10^{-6}. Values for r_p which do not depend on bound-state QED come from electron scattering experiments. Recent re-evaluation of all electron scattering data yielded a value of $0.895(18)$ fm[2], i.e. the relative uncertainty is as large as $2\,\%$.
In a 10-week measurement campaign in summer 2007, a new set of data was taken at the proton accelerator facility of the Paul Scherrer Institute in Switzerland. During the beamtime, the collaboration had to face several severe challanges so that the measured event rate did not meet the expected value. Nevertheless, a range of $2S \rightarrow 2P$ transition frequencies could finally be scanned in our laser spectroscopic experiment. Although, according to the current status of the analysis, the significance of the data is weak, it shows that we are on the right track. The re-gained experience together with a dramatically improved laser-system[3,4] and the perspective of an already approved and scheduled measurement-run in early 2009 makes us confident to complete this experiment successfully.

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Many-Atom Correlated States Produced via Cavity-Enhanced Nondemolition Measurement

I. Teper, G. Vrijsen, J. Lee, M. A. Kasevich

Physics Department, Stanford University, Stanford, CA 94305, USA

The maximal sensitivity possible with atomic clocks and interferometers using uncorrelated atomic ensembles is given by the standard quantum limit for projection measurements. For a phase read out via the relative populations in two states of an ensemble of N atoms, this leads to a signal-to-noise ratio (SNR) that scales as $\sqrt{N}$. The use of spin-squeezed states, which have reduced projection noise for certain collective spin observables at the expense of increased noise in conjugate observables, can exceed the standard quantum limit and approach the Heisenberg limit, for which the SNR grows as N [1].

We use a quantum nondemolition measurement of an ensemble of ^{87}Rb placed in a high-finesse optical cavity to create entanglement between the phase of the probe laser field and the collective atomic pseudospin. Analysis of the conjugate antisqueezing produced in the atomic ensemble after projecting out the probe field state shows that our protocol produces conditional spin squeezing in the atomic ensemble.

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Progress toward a measurement of the ^{225}Ra atomic electric dipole moment

W. L. Trimble[1], I. A. Sulai[1,2], P. Mueller[1], I. Ahmad[1], K. Bailey[1], M. Bishof[1,2], J. P. Greene[1], J. R. Guest[1], T. P. O'Connor[1], R. J. Holt[1], Z.-T. Lu[1,2], H. A. Gould[3]

[1]*Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[2]*Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[3]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

The best limits to date on T-inversion-symmetry-violating effects in nucleons come from the searches for an electric dipole moment in ^{199}Hg and the neutron. ^{225}Ra (I=1/2) is a particularly sensitive probe for new physics. The octupole deformation in this nucleus enhances the observable Schiff moment by a factor of a few hundred over lighter nuclei.[1] Since radium can be optically cooled and trapped, samples of atoms can be prepared, held for many seconds, polarized by optical pumping, and detected optically. A tabletop experiment using ^{225}Ra can, in principle, set more stringent limits on the EDM of the nucleus.[2]

We have constructed a magneto-optical trap (MOT) for radium using the the quasicycling $^1S_0 \rightarrow {}^3P_1$ ($\Gamma = 2\,\pi \cdot 380$ kHz) transition at 714 nm for slowing, cooling, and trapping. A second "repump" laser on the $^3D_1 \rightarrow {}^1P_1$ transition at 1428 nm prevents atoms from accumulating in low-lying metastable states $^3P_0$ and $^3D_1$. Surprisingly, one laser is sufficient to de-populate both of these metastable states, because the two metastable states are connected at a rate of 200 sec^{-1} by blackbody radiation at room temperature. This is fast enough to prevent the loss of atoms from the trap, and makes the trapping and cooling of the heaviest alkaline earth much simpler.[3]

Our apparatus uses 1 μCi and 1 mCi samples of ^{226}Ra ($t_{1/2}$=1600 years) and ^{225}Ra ($t_{1/2}$ = 15 days) respectively, and has achieved loading rates of 700 sec^{-1} and 20 sec^{-1}. There is room for improvement in the efficiency of trapping from the oven.

To make an EDM measurement, we will load radium atoms into a 100 μK-deep far-off-resonant optical dipole trap and transport them into a standing-wave optical dipole trap in a magnetically-shielded region 1 m from the MOT. This region will have a small (1 μT) constant magnetic field and a large (10 MV m^{-1}) reversible electric field. Radium atoms will then be polarized with a flash of circularly-polarized 483 nm laser light resonant with the $^1S_0 \rightarrow {}^1P_1$ ($\Gamma = 2\,\pi \cdot 27$ MHz) transition and the phase of nuclear precession detected by state-dependent absorption of a similar flash. A difference in the nuclear precession frequency with changing electric field would indicate an atomic EDM.

With improvements in trapping technique, high efficiency transfer of atoms into the measurement region, and optical readout of the atomic precession, we hope to achieve 10^{-26} e·cm sensitivity to the possible EDM of the ^{225}Ra atom.

This work is supported by the U. S. Department of Energy, Office of Nuclear Physics, under contract No. DE-AC02-06CH11357.

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Elimination of non-linear Zeeman splitting using AC Stark shifts

V. M. Acosta[1], K. Jensen[2], J. M. Higbie[1], M. P. Ledbetter[1], D. Budker[1,3]

[1]*Department of Physics, University of California, Berkeley, CA 94720-7300*
[2]*QUANTOP, Danish National Research Foundation Center for Quantum Optics, Niels Bohr Institute, Copenhagen University, DK 2100, Denmark*
[3]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720*

Optical magnetometers measure magnetic fields with high sensitivity without the use of cryogenics [1]. However, at geomagnetic fields, important for applications from detection of explosives to archaeology, Breit-Rabi mixing of Zeeman levels decreases magnetometer sensitivity by splitting the Zeeman resonance into many separate lines, leading to systematic dependence on sensor orientation ("heading error"). Several techniques for elimination of this nonlinear Zeeman splitting have been explored, involving manipulation of higher-order coherences [2] and a double modulation of the optical pumping light [3]. We present experimental results on a method of eliminating this systematic error, using the AC Stark shifts from an off-resonant light beam. The optimization of the light polarization and detuning of the Stark-shifting light is explored.

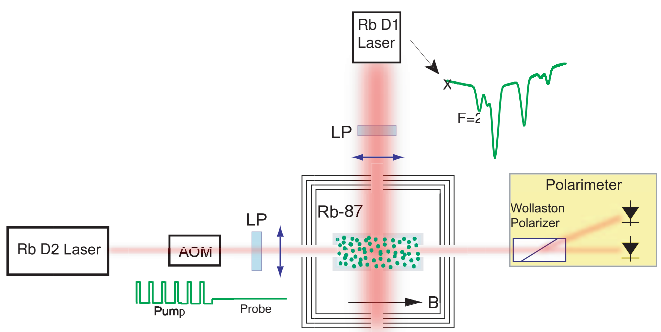

Figure 1: *Apparatus. Light from a Rb D2 laser is used to stroboscopically pump alignment in a Rb-87 paraffin coated cell. Weak cw light from the laser then probes the free induction decay of the optical rotation due to the induced linear dichroism. A Rb D1 laser far detuned from the Rb-87 resonance shifts the atomic levels, eliminating the nonlinear zeeman quantum beats. AOM–acousto-optic modulator, LP–linear polarizer.*

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Measurement of the Quadratic Zeeman Shift of ^{85}Rb Hyperfine Sublevels in a Cold Atom Interferometer

R. B. Li[1,2,3], L. Zhou[1,2,3], J. Wang[1,2], M. S. Zhan[1,2]

[1]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics,Chinese Academy of Sciences, Wuhan 430071,China*
[2]*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*
[3]*Graduate School of the Chinese Academy of Sciences, Beijing 100080, China*

Since the atom interferometer was demonstrated in 1991[1], it has been applied to the measurement of acceleration and rotation [2,3]. The quadratic Zeeman shift is considered a factor that influences the accuracy of measurement in the atom-interferometer gyroscope. Thus it is important to measure accurately the quadratic Zeeman shift of atoms in the cold atom interferometer. Although Paschen-Back effect has been studied in the strong magnetic field[4], the quadratic Zeeman Effect is difficult to observe in usual methods for the small value in the weak magnetic field. Based on our recent works[5,6], we investigated the hyperfine Zeeman sublevels of ^{85}Rb with the coherent population transfer by the stimulated Raman transition. The quadratic Zeeman shift is measured to be $\triangle\nu$=1296.8$\pm$3.3 Hz/G^2 for magnetically insensitive sublevels (5$\underline{S}_{1/2}$, $\underline{F}$=2, $\underline{m}_F$=0$\rightarrow$5$\underline{S}_{1/2}$, $\underline{F}$=3, $\underline{m}_F$=0) after the magnetic field compensation and the canceled ac Stark shift. Theoretical analysis is also carried out using the second-order perturb theory, which is in a good agreement with the experimental results in our measurement precision. This result provides the helpful data for improving the accuracy of the atom-interferometer gyroscope.

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New analytical relativistic formula for X-ray and gamma-ray Rayleigh scattering by K-shell electrons

A. Costescu[1], C. Stoica[1], S. Spanulescu[2]

[1]*University of Bucharest*
[2]*Hyperion University of Bucharest*

Considering the S-matrix element for elastic scattering of photons by ground state electrons and using the Coulomb-Green function for Dirac equation[1,2,3] we obtain the real part of Rayleigh amplitude up to the fourth order in αZ while the imaginary part is obtained in the sixth and seventh order in αZ. In order to achieve that, the first two iterations to the main term of the Dirac Coulomb Green function have to be taken into account. We point out that important logarithmic terms which are present in the imaginary part of the amplitude are given by the second iteration and involve the simpler Green function expression obtained by Martin and Glauber. For high atomic numbers, due to the specific behavior at small distances from the nucleus of the ground state Dirac spinor, some subtle relativistic effects are revealed near the photoeffect threshold.
Our formulae give very good predictions, within 4% for photon energies up to 5 MeV, comparing with accurate numerical relativistic calculations existing in the literature[4,5,6].
Via the optical theorem the imaginary part of the forward elastic scattering amplitude provides the photoeffect cross section and also the pair production cross section with the electron created in the K shell.
For low Z elements, the well known Sauter's formula is recovered as a rough approximation of the exact relativistic result. Our formulae contain all terms that lead, in the limit of infinite photon energy, to the corrective term due to Pratt[7]. Also, for forward scattering, in the high energy limit we confirm the expression given by Florescu and Gavrila[8] for the real part of the Rayleigh amplitude.
In the nonrelativistic limit, we get the analytical result involving all the multipoles and retardation terms for the angular distribution and photoeffect, without any spurious singularities.
Our formalism allows to include the screening effects which may be important near the photoeffect threshold, by using an effective nuclear charge Z_{eff} depending on the photon momentum transfer.
We point out that cross section for the K -shell electrons provides, in the high energy regime, the most important contribution to the total cross section of the whole atom.

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Renormalization and Universality of Van der Waals Forces

A. Calle Cordón, E. Ruiz Arriola

Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, E-18071 Granada. Spain

Van der Waals forces appear in the description of scattering and bound states and are of direct relevance in many physical contexts. We show how renormalization ideas can profitably be exploited in conjunction with the superposition principle of boundary conditions in the description of model independent and universal features of the Van der Waals force. Based precisely on this idea we develop a striking universality of direct relevance to this sort of systems.
Although, some of the displayed features are far more general than the Van der Waals case and depend solely on the characterization of potential scattering by two different and independent length scales, the renormalization of VdW forces is carried out explicitly, both for scattering as well as for bound states and we undertake an illustrative comparison of the renormalized theory with phenomenological potentials. The results suggest an appealing method to extract the scattering length directly from the knowledge of data as well as the long distance behaviour of the potential, i.e., the cross section at not too low temperatures. We also discuss under what conditions the long distance expansion can meaningfully be truncated.

Mechanical effect of photoassociation for metastable atoms: a new method to measure the scattering length

S. Moal[1], M. Portier[1], J. Kim[1,2], E. Arimondo[1,3], M. Leduc[1]

[1]*École Normale Supérieure, Laboratoire Kastler Brossel, 24 rue Lhomond, 75231 Paris Cedex 05, France*
[2]*Myongji University, Yongui, Korea*
[3]*Dipartimento di Fisica E. Fermi, Universitá di Pisa, Pisa, Italy*

Photoassociation (PA) of cold atoms provides detailed information on molecular systems such as binding energies or molecular lifetimes. In the PA process a colliding pair of free atoms is excited to a molecular bound state by a laser beam slightly detuned below the free-atom resonance frequency. In [1] and [2] we have used one and two photon PA signals to unambiguously determine the scattering length a of helium in the 2^3S_1 metastable state.
An usual detection method of PA is the measurement of trap losses. However alternative methods can be used which exploit the temperature rise or momentum transfer produced by PA. A fraction of the atoms resulting from the dissociation of the PA molecules remains trapped and transfers the energy and momentum acquired after the laser pulse absorption to the atomic cloud. The former process induces a temperature rise, studied for helium both experimentally [3] and theoretically [4] and theoretically for alkali atoms in [5] and in [6]. The latter process induces dipole oscillations of the atomic cloud in the direction of the PA laser beam, which are here studied for the first time.
We measured the amplitudes of these oscillations and relate them to the PA probability calculated with a model involving the interaction potential between the free atoms. From such a comparison we derived the s-wave scattering length a of helium metastable atoms. To improve the precision we eliminated the experimental uncertainty on the laser intensity incident on the cloud by comparing the results obtained by exciting several vibrational levels of the same molecular potential. A precise value for the a value is derived. This new and simple method provides results in excellent agreement with previous spectroscopic PA measurements based on atom losses or temperature rise.
The physical processes that produce the rise of temperature and momentum produced by PA on ultracold He atoms are discussed. From the measurement of the momentum exchanged in helium we derive the fraction of atoms that following a PA process do not escape from the trap.
The new photo-mechanical method introduced here is very precise and very simple from an experimental point of view. It requires an ultracold gas, not necessarily condensed, and a tunable laser whose frequency is tuned over few molecular resonant transitions. The present method may be transposed to other gases cooled and trapped in the μK range, even if the amplitude of the dipole oscillations decreases with the atomic mass.

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Broadening and Shifts of Autoionizing Series of Barium Induced by Rare Gas Collisions

K. S. Bhatia, M. Marafi

Department of Physics, Kuwait University, P.O.Box 5969, Safat 13060, Kuwait

Autoionizing series converging on BaII 5d$_{3/2}$ and 5d$_{5/2}$ have been excited directly from the BaI $^1S_0$ ground state using 2-photon absorption. Influence of the rare gas collisions on the series along with measurements of broadening and shift parameters will be presented. Our experimental procedure involved is the excitation of Ba vapours in a heat pipe. Autoionized states are populated by a tunable dye laser pumped by 15 ns excimer laser. The resonances are detected by thermoionic diode. Comparison of line profiles generated by stepwise excitation and those with direct 2-photon excitations will be presented. Mutual interactions of series belonging to 5d$_{3/2}$ and 5d$_{5/2}$ converging limits will be discussed.

Elastic Electron Scattering by Antimony Atom

B. P. Marinković[1,2], D. Šević[1,2], V. Pejčev[1,3], D. M. Filipović[1,4]

[1]*Institute of Physics, Pregrevica 118, 11080 Belgrade, Serbia*
[2]*The Advanced School of Electrical Engineering and Computing, 11000 Belgrade, Serbia*
[3]*Faculty of Natural Sciences, University of Kragujevac, 34000 Kragujevac, Serbia*
[4]*Faculty of Physics, University of Belgrade, P. O. Box 368, 11001 Belgrade, Serbia*

The low and intermediate energy electron scattering from metal atoms has been studied extensively recently. Detailed knowledge on the differential cross sections (DCSs) is important for understanding the basic interaction in the electron atom scattering processes.
A short review of our experimental work on electron interactions with metal atoms (Ca, Yb and Pb) has been published recently[1] Experimental and theoretical studies of elastic scattering by In and Ag atoms are on the way.[2]
The angular distribution of elastically scattered electrons was measured in the intermediate energy range up to 100 eV at scattering angles from 10^o to 150^o. The measurements were carried out using the perpendicularly crossed electron and atom beams. Electron spectrometer consists of hemispherical monochromator and analyzer. Elastically scattered electrons were analyzed and detected as a function of scattering angle at fixed electron-impact energy by a hemispherical electron energy analyzer and channeltron as a single-electron detector. Typical energy and angular resolutions were 60 meV and 2^o respectively.

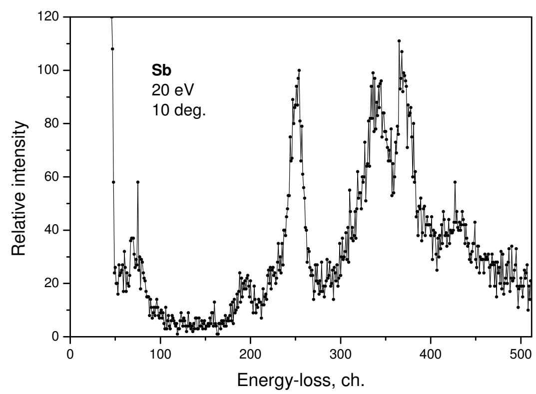

Figure 1: *Energy loss spectrum of antimony vapor obtained by heating of pure crystalline antimony at approximately 900 K.*

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A radio-frequency assisted d-wave Feshbach resonance in the strong field regime

B. Laburthe-Tolra[1], Q. Beaufils[1], T. Zanon[1], E. Maréchal[1], L. Vernac[1], A. Crubellier[2], J. C. Keller[1], O. Gorceix[1]

[1]*Laboratoire de Physique des Lasers, CNRS UMR 7538, Université Paris-Nord, 93430 Villetaneuse, France*
[2]*Laboratoire Aimé Cotton, CNRS UPR 3321, Université Paris-Sud, 91405 Orsay, France*

We report on the experimental study of a d-wave Feshbach resonance with optically trapped ultra-cold chromium atoms. A rather surprising manifestation of the strength of dipole-dipole interactions in chromium is the existence of relatively broad d-wave Feshbach resonances. The d-wave scattering cross-section of two atoms, usually vanishingly small at low temperature T because the atoms need to tunnel through a centrifugal barrier, is resonantly enhanced when a molecular level reaches the molecular dissociation limit.
We studied this magnetic-field-dependant resonance by measuring three-body losses. We find that the width Δ of the resonance (versus magnetic field B) varies very rapidly with T. In practice, we could not observe losses below $T = 2\ \mu$K, when $\Delta < k_B T$. We also perfomed a radio-frequency (rf) spectroscopy of the molecular level leading to the resonance for magnetic fields B close to the Feshbach resonance at B_r =8.2 G. Resonant losses are observed at rf angular frequencies $\hbar\omega = g_J \mu_B (B - B_r)$. We interpret our results in terms of an rf-assisted d-wave Feshbach resonance, in the strong field regime. The rf-assisted losses depend on the ratio of the rf Rabi angular frequency Ω to ω, and they are modulated by the first Bessel function $J_1\left(\frac{\Omega}{\omega}\right)$. This shows that the three-body loss process involves an incoming channel dressed by the rf field (the amplitude of the wave-function in the first order being $J_1\left(\frac{\Omega}{\omega}\right)$), resonant with the molecular level. This is similar to what was observed in the case of radiatively assisted collisions of Rydberg atoms[1].

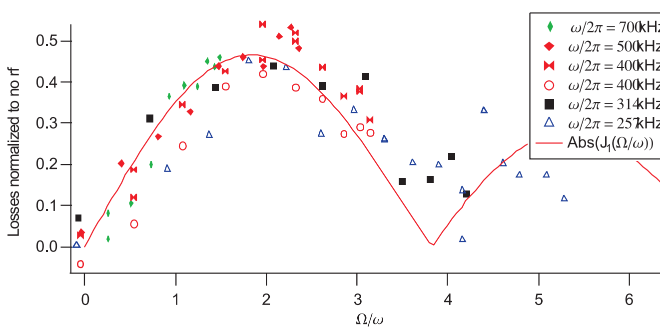

Figure 1: *Losses observed near the Feshbach resonance for different resonant rf frequencies. Irrelevant of ω and Ω, losses only depends on $\frac{\Omega}{\omega}$. We also plot $\left|J_1\left(\frac{\Omega}{\omega}\right)\right|$.*

[1]P. Pillet et al., Phys. Rev. A **36**, 1132 (1987)

An atomic Fresnel biprism interferometer.

G. Dutier[1], J. Grucker[1], J. Baudon[1], F. Perales[1], V. Bocvarski[2], J.-C. Karam[1], G. Vassilev[1], M. Ducloy[1]

[1]*Institut Galilée, Université Paris 13, Villetaneuse, F93430, France*
[2]*Institute of Physics - Belgrade, Pregrevica 118, 11080 Zemun, Serbia*

One has demonstrated, for atoms with internal angular momentum, an efficient coupling between atomic Zeeman states allowed by the quadrupolar component of the surface-induced van der Waals (vdW) interaction[1]. This exo-energetic, inelastic, "vdW - Zeeman" transition provides a tuneable (magnetic field intensity dependent) beam splitter which can be used in atomic interferometry. We theoretically illustrate the importance of this effect with the simplest interferometer, an atomic counterpart of Fresnel biprism[2]. Let us consider a velocity adjustable atomic beam (supersonic beam followed by a Zeeman slower) coming across two opposite surfaces (single slit of a nano-grating, see Fig 1). If the transverse coherence radius is large enough, the atom wave packets strongly inelastically diffracted by the two surfaces to an other magnetic sub-level will overlap at some distances from the slit and nonlocalised interference fringes are predicted. The calculation has been done for Ar* metastable atoms with such experimental constraints as the grating size (100nm period), applied magnetic field, roughness of the slit bars, velocity of the atoms (600 to 50 m/s). Via the interference pattern (Schlieren image), this device should give access to such novel information as the oscillating part of the vdW interaction transition amplitude. This basic configuration is by definition not sensitive to inertial effect (it contains no closed loop). As a next step, a transmission grating could be added to realize a new type of compact close interferometer.

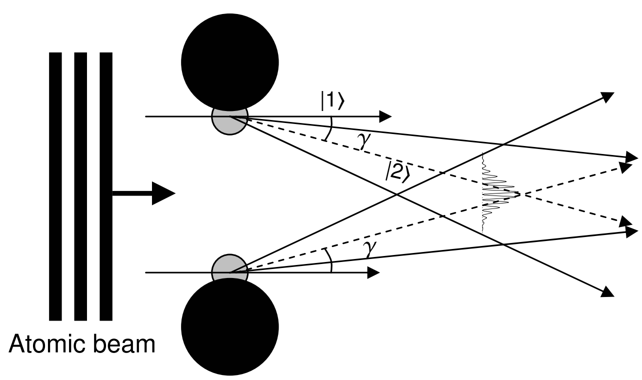

Figure 1: *The atomic Fresnel biprism interferometer principle. γ is the angular deviation induced by the passage from the $|1\rangle$ to the $|2\rangle$ magnetic sub-level.*

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Cold Collision Shift of Magnetic Resonance in Atomic Hydrogen Gas

J. Ahokas[1], J. Järvinen[1,2], S. Vasiliev[1]

[1] *Department of Physics, University of Turku, 20014 Turku, Finland*
[2] *Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca NY 14850, USA*

We report on an experimental study of magnetic resonance line shifts in cold spin-polarized atomic hydrogen gas (H↓). We have found that for identical H atoms there are large discrepancies between the experimental line shifts and the ones calculated from the mean-field energies. The line shifts have been measured for two- and three-dimensional H↓ samples, stabilized in a 4.6 T magnetic field at temperatures of 70 to 500 mK. In this temperature range, due to the light mass of the H atom, the thermal de Broglie wavelength Λ_{th} is much larger than the s-wave scattering length $a \approx 0.07$ nm. Therefore, atoms are interacting in the cold collision regime and the exchange interaction leads to a shift of the resonance lines called the cold collision or clock shift (CS), which is well known in the field of atomic frequency standards.

A two-dimensional atomic hydrogen gas is created by adsorption of atoms on a superfluid ^{4}He film covering the walls of the sample cell. At temperatures below 100 mK, surface densities of $\sigma = 5 \times 10^{12}$ cm^{-2} can be achieved by the thermal compression method.[1] In the experiments, electron-spin and nuclear magnetic resonance were used to separate the effects of exchange and dipolar interactions on the resonance line shifts.[2] We found that the CS in two-dimensional hydrogen gas polarized to a single hyperfine state is nearly 300 times smaller than expected from the mean-field theory.

In a separate measurement we studied electron-spin resonance line shifts in three-dimensional H↓ gas. In this case, we found that in a mixture of different hyperfine states, the CS is in much closer agreement with the mean-field theory. This is in contrary to the case of doubly polarized H where we see the shift 50 times smaller than predicted.

We propose the symmetrization requirements of the wavefunctions of colliding H atoms[3] as an explanation for the discrepancies. The different symmetrization requirements for different spin states modifies the two-atom correlations, and thus changes the mean-field interaction energy. When the mean-field energies are calculated taking the symmetrization into account, we found that the calculated line shifts are in good agreement with the experiment.

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Theoretical study of an excitation blockade in ultracold Rydberg gases

J. Stanojevic[1,2], R. Côté[2], J. M. Rost[1]

[1] *Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Str. 38, 01187 Dresden, Germany*
[2] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*

We have derived closed formulae[1] for the excitation fraction and the correlation function between Rydberg atoms for the most important cases of excitation pulses and interactions. We have compared our formulae with the recent numerical and experimental results, including the new observation of the blockade effect of Rydberg excitation in a Bose-Einstein condensate[2]. In all considered examples, our formulae described well the numerical and experimental findings.

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Towards thermal equilibrium of atomic polariton states

U. Vogl, J. Nipper, C. Bolkart, L. Karpa, M. Weitz

Institut für Angewandte Physik, Universität Bonn, Germany

Thermal equilibrium is a prerequisite for most known phase transitions, as Bose-Einstein condensation of dilute atomic gases. Recently, phase transitions of coupled particle-light degrees of freedom have been investigated in the framework of polariton quasiparticle condensation. Experimentally, exciton polariton systems gave compelling evidence for a condensation, however the short polariton lifetimes of around a ps arose the question whether the system is fully thermalized[1]. In the area of atomic physics, extremely long coherence times of excitations are readily achieved. However, the lack of a sufficiently fast thermalization process has so far prevented equilibrium thermodynamics of coupled atom-light states to be a useful concept.

Here we show work directed towards thermal equilibrium of atomic polariton states. Polaritons have been investigated both in Lamda-type levels schemes, yielding so called dark polaritons, and in two-level systems. Particularly attractive seems the use of an ultrahigh pressure buffer gas system, where frequent collisions with the buffer gas can cause rapid thermalization of a (two-level) coupled atom-light system.

Fig.1 shows spectra for a rubidium atomic sample at up to 500 bar of buffer gas pressures[2]. The buffer gas induces a spectral linewidth of a few nanometers for the D-lines. At high optical power of the exciting continuous-wave laser source, the spectra are broadened by additional power broadening to values exceeding the thermal energy $k_B T$ in the heated gas cell. In this regime, we observe a strong blue asymmetry of the lines. The spectral asymmetry increases further when extrapolating our data towards infinitely high excitation intensity. We interpret our results as evidence for the coupled atom-light states ("dressed states") to approach thermal equilibrium, with the thermalization being due to frequent rubidium-buffer gas collisions. Notably, equilibrium is achieved in the presence of an external monochromatic driving optical field.

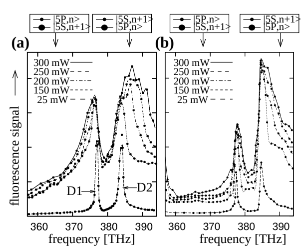

Figure 1: *Fluorescence spectrum of rubidium D-lines at (a) 500 bar argon and (b) 400 bar helium buffer gas pressure for different driving optical beam powers. The relative population of dressed states on the red and blue side of the transition respectively are indicated in the small drawings on the top of the figure.*

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Charge Transfer Between Cold Atoms and Ions

M. Cetina, A. Grier, F. Oručević, T. Pruttivarasin, I. L. Chuang, V. Vuletić

Center for Ultracold Atoms, MIT, Cambridge, MA

We measure the collisional cross-section and rate constant of the near-resonant ^{174}Yb and ^{172}Yb charge-transfer process at energies corresponding to temperatures between 500mK and 50K. The neutral atoms are trapped in a magneto-optical trap (MOT) near the Doppler-limited temperature of 680 mK. The ions are confined in a planar Paul trap with a secular frequency of 50 kHz, Doppler cooled, and spatially overlapped with the neutral atoms. We measure a rate constant of $0.6 \times 10^{-9} cm^3/s$ (to within 1.5x), matching the Langevin cross-section with 50% charge exchange probability.

Inelastic Collisions in the Metastable $^3P_0$ $^3P_2$ States of ^{88}Sr

P. G. Mickelson, Y. N. Martinez de Escobar, S. B. Nagel, A. J. Traverso, T. C. Killian

Rice University, Houston, Texas 77005, USA

We measure the inelastic loss rates of the metastable $^3P_2$ and $^3P_0$ levels of ^{88}Sr. Our atom sample is trapped in a far-off-resonance dipole trap operating at 1064 nm, and we use repumper lasers at 679 nm, 688 nm, and 3.32 μm to shuffe atoms into and out of the various metastable levels. At 12 μK, the 2-body loss rates, including both elastic and inelastic losses, are about 4×10^{-11} for the $^3P_2$ level and about 1.25×10^{-11} for the $^3P_0$ level. The value of the $^3P_2$ lifetime qualitatively agrees with the theoretical values calculated in Kokoouline et al.[1] and is consistent with measured rates of the $^3P_2$ states in Ca[2] and Yb[3]. Obtaining such samples of ultracold atoms in the metastable states may enable improved frequency standards and allow the possibility of quantum degeneracy in an alkaline earth element.

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Theoretical Investigations on Ion-Atom collision

M. Purkait

Department of Physics, Ramakrishna Mission Residential College, Narendrapur, Kolkata-700103, India

Recently much research has been done to understand the mechanism of electron correlation experimentally and theoretically. Incorporating the role of electron correlation in ion-atom collisions, the cross sections for phenomena such as double excitation, double ionization, double and single charge transfer closely compete with experiment. We have calculated the different channel cross sections by using Four-Body Boundary Corrected Continuum Intermediate State (BCCIS-4B) approximation. As ions of helium, Lithium, Berillium, Boron and Carbon atoms are important species for their applications in different branches of physics. The following reactions are studied.

$$\begin{aligned} A^{q+} + He(1s^2) &\rightarrow A^{q+} + He^{**}(nl, n'l') \text{ (Double-electron excitation)} \\ &\rightarrow A^{(q-1)+} + He^{+}(1s) \text{ (Single charge transfer)} \\ &\rightarrow A^{(q-2)+} + He^{++} \text{ (Double charge transfer)} \end{aligned}$$

The transition amplitude for any processes may be written as

$$\begin{aligned} T_{if} &= <\Psi_f|V_f|\Psi_i^+> \text{ (Post form)} \\ &= <\Psi_f^-|V_i|\Psi_i> \text{ (Prior form)} \end{aligned}$$

where $\Psi_i^+(\Psi_f^-)$ is the scattering solution of the total Hamiltonian. The complexity of the four body formalism may be due the presence of three coulomb function in the transition amplitude, which has to be tackled. Again the transition amplitude in nine dimensional integral has to be reduced as far as possible. Finally cross section may be evaluated by numerical integration as accurately as possible. The essence of the method lies in the fact that (i) total scattering wave function satisfies the proper boundary condition, (ii) perturbing potential is faster falling than coulomb potential, (iii) intermediate continuum states of the electrons have been taken into the formalism. This may be the reason to expect better results over other theoretical findings in the intermediate to high energy region.

Study of the Rydberg state excitation of few cold Rb atoms in a dipole trap

K. Nakagawa[1,2], Z. Zuo[1], M. Fukusen[1], Y. Tamaki[1], T. Watanabe[1]

[1] *Institute for Laser Science, Univ. of Electro-Communications, Tokyo, Japan*
[2] *Japan Science and Technology Agency, CREST, Saitama, Japan*

Recently cold Rydberg atoms are of great interest due to their strong dipole-dipole interaction which will allow to realize a fast quantum gate with neutral atoms [1]. A long-range dipole-dipole interaction between Rydberg atoms can be used to realize an entanglement between spatially separated two atoms via the blockade of simultaneous excitation of two atoms to the Rydberg state. So far this dipole blockade effect of Rydberg atom excitation has been mainly studied with a rather macroscopic number of laser-cooled atoms in a MOT. The study of the Rydberg-Rydberg interaction on the coherent excitation of very few atoms was reported very recently [2]. Thus further investigations along this direction will open the way to the realization of the atom-atom entanglement and the proposed quantum gate.

In this poster presentation, we will present our recent investigation towards the realization of the dipole blockade between two cold ^{87}Rb atoms in an optical dipole trap. For the study of the Rydberg atom interaction, we have developed a versatile optical dipole trap [3]. We can trap a single or a very few (< 5) ^{87}Rb atoms in a MOT or an optical dipole trap with a long life time of more than 10 s. For the excitation of ^{87}Rb atoms to highly excited Rydberg state with principal quantum number n > 50, we use two-photon transition with 780 nm and 480 nm lasers. Using a two-photon absorption spectroscopy in a Rb cell [4], a 480 nm laser frequency is stabilized to the Rydberg state transition within 100 kHz. We have also employed an optical frequency comb technique to determine the absolute optical frequency of the Rydberg state transition with a high accuracy. In our preliminary experiment with these trap and lasers, we have observed the Rydberg state excitation of few Rb atoms in a MOT and a dipole trap from the measurement of the trap loss. We are investigating the spectral width and shift of the two-photon transition to the Rydberg state to study the interaction between Rydberg atoms.

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Magnetic trapping and anomalous inelastic collisions in the few-partial-wave regime

N. Brahms[1,3], B. Newman[1,3], C. Johnson[1,3], D. Kleppner[1,3], T. Greytak[1], J. M. Doyle[2,3]

[1]*Massachusetts Institute of Technology, Cambridge, MA 02139*
[2]*Harvard University, Cambridge, MA 02138*
[3]*Harvard/MIT Center for Ultracold Atoms, Cambridge, MA*

Collisional physics in the few-partial-wave regime can display rich structure and determine the efficacy of buffer gas cooling and trapping. We explore inelastic Zeeman-state-changing collisions in the few-partial-wave regime between 300 mK and 1 K. We trap up to 40 trillion copper (Cu) or silver (Ag) atoms using buffer gas loading, and observe elastic and inelastic collisions with ^{3}He. Only 1 in 10^6 collisions result in a change of the atom's Zeeman state. For Ag, we observe an anomalous T^6 temperature dependence of the inelastic cross-section (see Fig. 1). This dependence is inconsistent with a standard theoretical treatment based on the spin-rotation interaction. Collisions of nickel (Ni) and iron (Fe) are observed with ^{3}He, with observed elastic-to-inelastic collision ratios as large as 5×10^3. Additionally, we trap up to 10 trillion dysprosium (Dy) and holmium (Ho) atoms, with lifetimes as long as 40 s. By removing the ^{3}He buffer gas from our trapping region using a fast cryogenic valve, we observe inelastic intra-atomic Dy–Dy and Ho–Ho collisions. These collisions are sufficiently rare that evaporative cooling of these atoms from the multiple-partial-wave regime to ultracold temperatures may be possible.

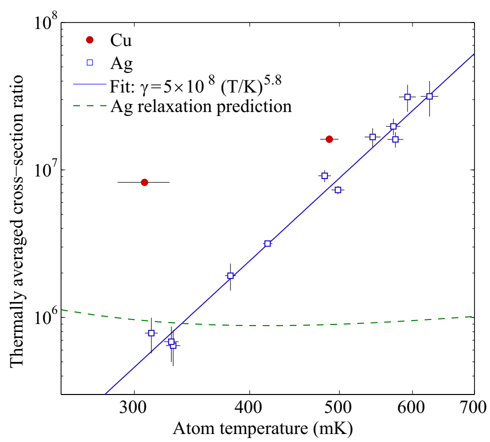

Figure 1: *Ratio γ of elastic to inelastic collision cross-sections vs. temperature for the Cu–^{3}He and Ag–^{3}He systems.*

Coherent Control of Ultracold Collisions with Nonlinear Frequency Chirps on the Nanosecond Timescale

J. A. Pechkis, J. L. Carini, C. E. Rogers III, P. L. Gould

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

We report on measurements of ultracold collisions between Rb atoms induced by frequency-chirped laser light. Either positive or negative chirps, centered at a variable detuning below the atomic resonance, sweep over 1 GHz in 100 ns. If the light is resonant with an attractive atom-pair potential at some point during the chirp, the pair is excited, potentially resulting in trap loss. In previous work with linear chirps,[1] the negative chirp yielded a lower collisional loss rate β than the positive chirp at certain center detunings. We attribute this to the fact that the negative chirp follows the excited-state wavepacket trajectory and, thus, can de-excite the wavepacket, coherently blocking the collision. In the present work, we use nonlinear chirps, either concave-down or concave-up. For the negative chirp, we find a dependence on the details of the nonlinearity at center detunings Δ where coherent collision blocking occurs (see Fig. 1). In particular, the concave-down chirp yields a higher β than the linear and concave-up chirps, indicating the importance of the shape of the frequency chirp on the excited-state wavepacket dynamics. This work is supported by DOE.

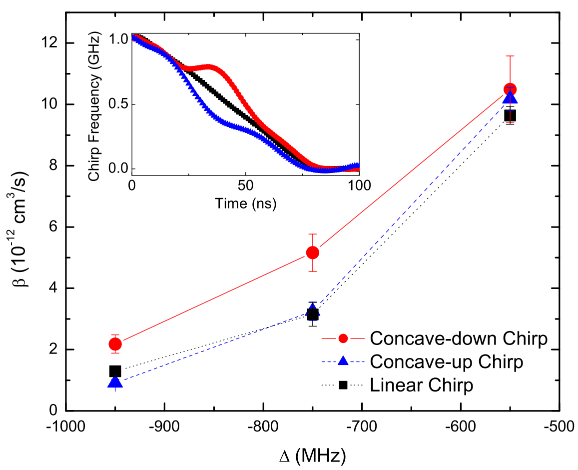

Figure 1: *$\beta(\Delta)$ for negative, nonlinear frequency chirps. The concave-down chirp yields a higher β than linear and concave-up chirps at Δ = -750 MHz. The inset shows the various chirp shapes. The 40 ns FWHM pulses are centered at 40 ns.*

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Energy Relaxation in Collisions of Atomic Particles

P. Zhang[1], V. Kharchenko[1,2], A. Dalgarno[1]

[1] *ITAMP, Harvard-Smithsonian Center for Astrophysics*
[2] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*

The energy distribution function is critical to the determination of the physical and chemical consequences of the presence of hot atoms moving in a thermal bath, as may occur broadly in applications of plasma physics, astrophysics and chemical physics. In addition, the energy relaxation process is important in cooling and trapping atoms and molecules. Theoretical treatments beyond the hard-sphere approximation are necessary for the cases where anisotropic scattering is dominant. Energy relaxation is investigated for different atomic gases and their isotopes, specifically for the astrophysically interesting processes of thermalizing energetic H (D) or O atoms in O or H (D) bath gases. Quantal calculations, explicitly considering the angular and energy dependent scattering processes, confirm that two times scales characterize the equilibration, one a short time, in which the isotropic energy distribution relaxes to a Maxwellian-like shape at some time-dependent effective temperature, and the second, a longer time in which the relaxation preserves a Maxwellian distribution and its effective temperature decreases continuously to the bath gas temperature. The formation and preservation of a Maxwellian distribution does not depend on the projectile to bath gas atom mass ratio, contrary to the hard-sphere predictions. This two-stage behavior arises due to the dominance of small angle scattering and small energy transfer in the collisions of neutral particles.

Generation of Nanosecond-Scale Frequency-Chirped Pulses with Fiber-Based Phase and Amplitude Modulators

C. E. Rogers III, M. J. Wright, J. L. Carini, J. A. Pechkis, P. L. Gould

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

We report on producing nanosecond-timescale pulses of laser light whose frequency is arbitrarily chirped and whose amplitude is arbitrarily controlled. The chirp is achieved by sending the output from a 780 nm diode laser through a fiber-based electro-optical phase modulator within a fiber delay loop. Upon exiting the fiber, the light has accumulated the desired time-dependent phase. It then re-injection locks the diode laser, thus maintaining the high optical power. Larger phase modulations can be accumulated by using multiple passes through this loop, re-injection locking after each pass. We are able to produce arbitrary chirps by driving the phase modulator with an arbitrary waveform generator[1]. Currently, we have been able to achieve chirp rates up to approximately 100 GHz/μs as shown in Fig. 1(a). To produce an arbitrary pulse amplitude, the light is sent through a fiber-based electro-optical amplitude modulator, driven with an arbitrary waveform generator. Using this technique, we have been able to achieve pulses as short as 4 ns FWHM as shown in Fig. 1(b). Such pulses will be useful in controlling collisions between ultracold Rb atoms. This research is supported by the U.S. Department of Energy.

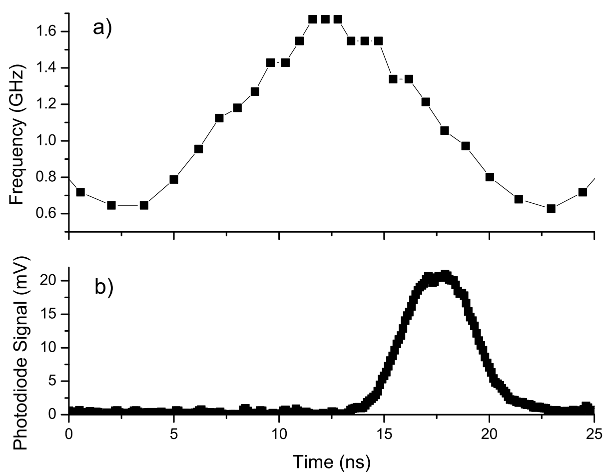

Figure 1: *(a) A 1 GHz linear frequency chirp in 10 ns. (b) The corresponding 4 ns Gaussian pulse selecting out the center of the negative chirp.*

[1] C.E. Rogers III, et. al., J. Opt. Soc. Am. B **24**, 1249-1253 (2007)

Photoassociation spectroscopy of cold metastable neon

R. D. Glover, D. E. Laban, W. C. Wallace, R. T. Sang

Centre for Quantum Dynamics, Griffith University, Brisbane, Queensland, Australia

Photoassociation spectroscopy of cold atoms has been used to study the long range interactions between atoms. It has been used as a tool to measure the lifetimes of excited states and test theoretical calculations of molecular states[1]. Additionally, photoassociation spectroscopy has enabled precise measurement of the s-wave scattering length which is crucial for the successful production of Bose-Einstein condensates[2]. Photoassociation is a process where two atoms approaching an unbound state potential absorb a photon. The atoms can then couple to an excited bound state in an electronic potential and form a molecule.

In order to produce a photoassociation spectrum, a low intensity photoassociation probe beam is used to illuminate the trap. The beam is red detuned from the standard cooling transition in order to induce photoassociation. Scanning the probe laser frequency will then excite different vibrational-rotational states in the excited bound molecular potential. When the laser frequency is tuned to a photoassociative resonance, trap losses will increase due to the formation of molecules. Observation of the spectrum is generally by measuring the loss of atoms in the trap, either by measuring fluorescence or ion production.

Photoassociation spectra have been experimentally measured for metastable helium $^3S_1$ state[3,4]. We will be presenting preliminary data for the photoassociation spectrum of metastable neon in the $^3P_2$ state using a magneto-optical trap.

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Long-range Wells in Rydberg-Rydberg Potential Curves

N. Samboy[1], J. Stanojevic[2], R. Côté[1]

[1]*Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[2]*Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Str. 38, 01187, Dresden, Germany*

We explore the long range interaction of Rydberg atom pairs, including spin-orbit coupling and fine structure, which lead to a study of l-mixing. By studying the effects of l-mixing, we find that some of the resulting potential curves exhibit wells deep enough to support bound states. We investigate the properties of these wells as well as the influence that small electric fields may have on these curves.

The Role of Scattering Lenght in Ultracold Interactions of Bose-Einstein Condensation

Secil Oral, Abidin Kilic

[1] *Department of Physics, Anadolu University, Eskisehir, Turkey*

The quantity as is known as the scattering lenght and is a fundemental input to theories of a dilute gas of atoms. In the dilute gas, the scattering lenght provides all of the information needed to calculate the change in the energy of the gas due to the interactions between the particles. The interaction is repulsive for positive or attractive for negative scattering lenght. Also, the true interaction pottential has many bound states irrespective of the sign of as. In the limit of low scattering energies, the additional energy is stored in the increased kinetic energy of the particles produced by the boundry condition of a node at r =as. At ultralow temperatures, the scattering lenght can be much larger than the hard-core size of the atoms assumed in kinetic theory for room-temperature atoms. Because of this large scattering lenght, collisional relaxation to thermal equilibrium is relatively quick compared to the distance between atoms - a required condition fort the gas to be weakly interacting or, equivalently, for the condensate fraction to be large. To estimate the scattering lenght, one needs very precise knowledge of the interatomic potential. For hydrogen, as can be calculated directly from molecular quantum mechanics. For alkali atoms, the estimation of as has relied on the development of new spectroscopic methods, particularly photo association spectroscopy. The theoretical and experimental technologies that now exists have yielded a very precise understanding of the interactions between ultracold atoms, which provides a crucial advantage in analyzing assemblies of Bose-Einstein condensed atoms. The scattering lenght can be accurately determined and not treated as an adjustable parameter.

Interaction phenomena in ultracold Rydberg gases

T. Amthor, C. Giese, C. Hofmann, J. Denskat, W. Sprenger, H. Schempp, M. Reetz-Lamour, M. Weidemüller

Physikalisches Institut, Universität Freiburg, Germany

We present experimental results and model calculations on coherent and incoherent phenomena in ultracold interacting Rydberg gases.

The first part focuses on the excitation process to Rydberg states. Long-range interactions among Rydberg atoms can cause both suppression and enhancement of excitation. Measurements and models for both effects based on van der Waals and dipole-dipole interactions are presented. Coherence in the excitation to Rydberg states is shown by direct observation of Rabi cycles[1].

Secondly, we present spectroscopic and time-resolved measurements which show that the interaction-induced motion is the cause for plasma formation out of Rydberg gases. For attractive interaction potentials this is easily understood, as atom pairs prepared at short distances experience strong attractive forces leading to collisional ionization[2]. The ionization dynamics of gases initially prepared in states with purely repulsive interaction is also discussed. The system is well described in terms of a Monte Carlo model including many-particle aspects and mechanisms for state redistribution to overcome repulsive forces[3].

As a third topic the resonant energy transfer in unordered and ordered systems of Rydberg atoms is discussed. The dynamics of energy transfer in unordered clouds is investigated experimentally and compared to a many-particle model[4]. As an outlook to future experiments calculations of exciton survival probabilities in regularly structured systems with excitation traps are presented[5].

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Series of doubly-excited states $^1S^e$ of Li^+ below the N=2 threshold of Li^{2+} *

T. T. Gien, K. Nguyen

Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. Johns, NL, A1B 3X7 Canada

The Harris-Nesbet variational method[1] for electron-Li^{2+} scattering[2] was considered for an accurate calculation of singlet S-wave phase shifts at energies below the N=2 threshold of Li^{2+} which were then used to determine the positions and widths of the singlet S-wave doubly-excited states $^1S^e$ of Li^+ below this threshold by fitting them to the Breit-Wigner formula. In order to detect high-lying doubly-excited states $^1S^e$ lying close to the threshold, we had to consider a fairly large basis set covering a wide spatial range.

We succeeded in determinining a significantly great number of doubly-excited states $^1S^e$ formed below the N=2 threshold of Li^{2+} with this alternative method of calculation. Because of the high accuracy of our method, we were able to locate, for the first time, at least four of these doubly-excited states which are of small width and lying extremely close to the N=2 threshold (and thereby, very difficult to determine). The positions and widths of the doubly-excited states determined by us were compared with those made available by other research groups using completely different numerical methods. We were also able to graphically present all the doubly-excited states determined by us. This confirms the definite existence of these doubly-excited-state resonances in the energy distributions of cross section and phase shift.

Detailed description of this work and its complete results will be presented at the conference with discussion.

*This research work is supported by the NSERC of Canada

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[2] T. T. Gien, J Phys B **35**, 4475 (2002), *ibid* **36**, 2291 (2003), *ibid* **41**, 035003 (2008).

Cold Titanium-Helium Collisions

Mei-Ju Lu, Kyle S. Hardman, Jonathan D. Weinstein

Department of Physics, University of Nevada, Reno NV 89557, USA

Fine-structure changing collisions have long been of experimental and theoretical interest due to the role they play in the cooling of diffuse interstellar gas and planetary atmospheres. Typical rate coefficients for fine-structure relaxation for atoms such as oxygen, carbon, silicon, and aluminum in collisions with noble gases or atomic hydrogen range from 10^{-12} to 10^{-10} cm^3 s^{-1}. We have experimentally measured inelastic collisions in the $[3d^2 4s^2]\ ^3F_J$ electronic ground state of atomic titanium, which has fine-structure levels J=2,3, and 4.
We produce atomic titanium by laser ablation and cool it with a cryogenic helium buffer-gas. The cold atoms diffuse to the cell walls where they adsorb; we observe titanium lifetimes up to a few seconds. We first prepare the atomic internal state by optical pumping, and then watch the atoms return to thermal equilibrium by inelastic collisions. From the rate of return and the helium density, we determine collisional cross-sections.

T(K)	$k_{3\rightarrow 2}$ (cm^3 s^{-1})	$\bar{\sigma_d}$ (cm^2)	k_m (cm^3 s^{-1})
5.2	$(4.4 \pm 0.7) \times 10^{-15}$	$(1.1 \pm 0.3) \times 10^{-14}$	$(1.2 \pm 0.6) \times 10^{-13}$
9.9	$(5.3 \pm 0.8) \times 10^{-15}$	$(8.6 \pm 2.3) \times 10^{-15}$	
15.6	$(7.7 \pm 1.2) \times 10^{-15}$	$(7.7 \pm 2.1) \times 10^{-15}$	
19.9	$(9.8 \pm 1.5) \times 10^{-15}$	$(7.3 \pm 2.0) \times 10^{-15}$	

Table 1: Ti–He collision J-changing rate coefficient $k_{3\rightarrow 2}$, thermally-averaged diffusion cross-section $\bar{\sigma_d}$, and m-changing rate coefficient k_m (measured at 3 Gauss), as measured at different temperatures T.

The Ti–He fine-structure-changing rate coefficient is significantly smaller than for collisions of non-transition-metal atoms with noble gases. This is attributed to the submerged-shell structure of titanium, and is similar to the suppression of m-changing collisions previously observed by Hancox et. al.[1] We also measured m-changing collisions at low magnetic field, and found a rate coefficient which is an order of magnitude larger than their measurement at high-field[1], suggesting this inelastic collision process has a strong field dependence.
Our experimental technique should be applicable to measure a wide variety of inelastic atom–helium or molecule–helium collisions; we expect to be able to measure inelastic collisions with rate coefficients ranging from 10^{-10} to 10^{-17} cm^3 s^{-1}.

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Inelastic Titanium-Titanium Collisions

Mei-Ju Lu, Vijay Singh, Jonathan D. Weinstein

Department of Physics, University of Nevada, Reno NV 89557, USA

We have measured inelastic ground-state titanium–titanium collisions at 5 Kelvin. The electronic ground state of titanium is $[3d^2 4s^2]\,{}^3F_J$; its nonzero orbital angular momentum results in an anisotropic interaction potential. In general, anisotropically-interacting atoms are expected to have large inelastic collision rates; we measure both fine-structure changing collisions (J-changing collisions) as well as Zeeman relaxation collisions (m-changing collisions).

We produce atomic titanium by laser ablation, and cool it by cryogenic helium buffer-gas cooling. We can produce titanium atom numbers up to 10^{15}, at densities up to 10^{12} cm^{-3}. We use laser absorption spectroscopy to measure the J state population of our atoms, as well as their polarization. We use optical pumping to perturb the atoms from thermal equilibrium, and watch the atoms return to equilibrium by inelastic collisions.

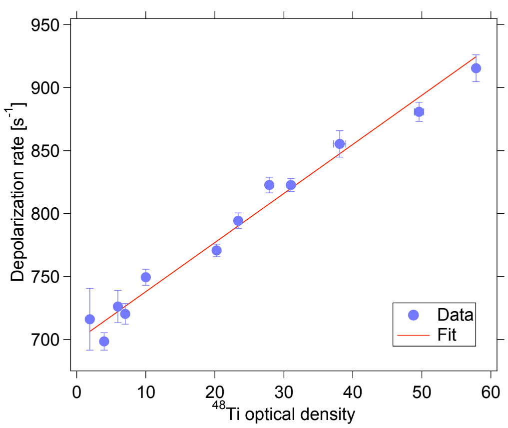

Figure 1: ^{50}Ti depolarization rate as a function of titanium density. (Taken at helium density 7×10^{15} cm^{-3}.) The offset is due to Ti–He m-changing inelastic collisions, the slope is due to Ti–Ti m-changing collisions.

We measure J-changing and m-changing collision rate coefficients of the order of 10^{-10} cm^3 s^{-1} for ^{50}Ti colliding with the other titanium isotopes, with an m-changing rate slightly larger than the J-changing rate. Unlike Ti–He collisions, which exhibit a suppression of inelastic collision rates due to the "submerged shell" structure of titanium, no evidence of suppression is observed here.

Because of the high densities produced, we expect this technique to be applicable to measuring a variety of inelastic atomic and molecular collisions, as well as the the measurement of cold chemical reactions.

Laboratory Astrophysics: Simulation of Cometary X-ray Spectra from Collisions of keV He-like O, N and Ne ions with Gases

K. Miller[1], W. W. Smith[1], Q. C. Kessel[1], V. Kharchenko[1], J. Simcic[2], A. Chutjian[2]

[1] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[2] *Jet Propulsion Laboratory/Caltech, Pasadena, CA, 91109, USA*

In 1996, the ROSAT satellite detected soft x-ray emission from the atmosphere of comet Hyukatake.[1] Subsequently, Cravens [2]proposed that these x rays, seen from all later comets, are due to charge exchange into excited states of keV highly-charged ions (C, N, O, Ne, S, Si, Fe, etc.) streaming from the Sun onto comet gases, e.g. H_2O, CO_2 and CO (solar-wind charge exchange or SWCX mechanism). We used JPLs Highly-Charged Ion Facility [3], and a UConn XUV spectrometer equipped with an XUV CCD camera, to measure line emission spectra from these ion-beam – gas collisions, simulating comet x-ray spectra observed from space, but with much higher resolution (0.05nm).
We compare observed lab spectra from three keV-energy He-like ions colliding with CO gas, yielding mostly Li-like ion XUV emission lines after one-electron transfer. Synthetic spectra are fitted, using the Coulomb over-the-barrier (OBM) model[4],to estimate the initial *(n,l)* populations. We can find the *l* and *n*-dependence of the cross sections from the spectra. The goal is both a fundamental understanding of these ion-neutral collisions and the development of diagnostics for sensing from space: comet composition, solar-wind abundances and ion velocity variations with time and solar latitude.
For 2.25 keV/u O^{6+} on CO, the OBM gives $<n>$ = 4.5, and we find the dominant electron-transfer excitations are to the O^{5+} 4*s,p,d,f* and 3*s,p,d* states, roughly consistent with the OBM predictions. The *l*-dependence of the initial populations appears to be approximately statistical, but theory for the H-like case shows a velocity dependence that suggests the need for further study in the Li-like case also.
He-like ions N^{5+} and Ne^{8+} on CO gas: in the N^{5+} case, the OBM predicts initial excitation to $<n>$ = 3.7, implying mostly n = 4 and some n = 3 initial excitation. The data show that the dominant transitions in the emission spectra are indeed from n = 3,4 *s,p,d* states (and possibly 4*f*).
In the Ne^{8+} case, the model gives $<n>$ = 5.9, so we predict projectile excited 6*l* states after collision. The spectra show that dominant emission lines are at 6.3, 16.7 and 17.2 nm, originating from 6*l* states; further investigation of the *l* dependence is needed. In sum, for He-like projectiles the OBM gives a remarkably good qualitative explanation of the *n,l* dependence of SWCX line cross sections.[5,6]

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[6] This research was supported by NASA grant NCC5-601 and at JPL by agreement with NASA.

Quantum reflection of helium atom beams from a microstructured grating

B. S. Zhao[1], S. A. Schulz[2], S. A. Meek[1], G. Meijer[1], W. Schöllkopf[1]

[1]*Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany*
[2]*Institut für Quanteninformationsverarbeitung, Universität Ulm, Ulm, Germany*

We observe high-resolution diffraction patterns of a thermal-energy helium-atom beam reflected from a microstructured surface grating at grazing incidence. The grating consists of 10-μm-wide Cr strips patterned on a quartz substrate and has a periodicity of 20 μm. Fully-resolved diffraction peaks up to the 7^{th} order are observed at grazing angles up to 20 mrad. With changes in de Broglie wavelength or grazing angle the relative diffraction intensities show significant variations which shed light on the nature of the atom-surface interaction potential.

As can be seen in Fig. 1 the probability for coherent reflection of a He atom from the Cr surfaces increases by two orders of magnitude when the normal component k_{perp} of the atom's wave vector is decreased from 0.3 to less than 0.02 nm^{-1}. A kink at $k_{\text{perp}} \simeq 0.12$ nm^{-1} separates a slow simple exponential decrease at larger k_{perp} from a steep decrease at smaller k_{perp}. The steep decrease cannot be explained by classical reflection from the surface, but it is described well by a simple 1-dimensional model for quantum reflection at the long-range attractive Casimir-van der Waals potential. Further support for quantum reflection is given by the observed reflection probabilities of weakly bound He trimers (10 μeV binding energy) and Ne atoms, which are both well described by the quantum reflection calculation.

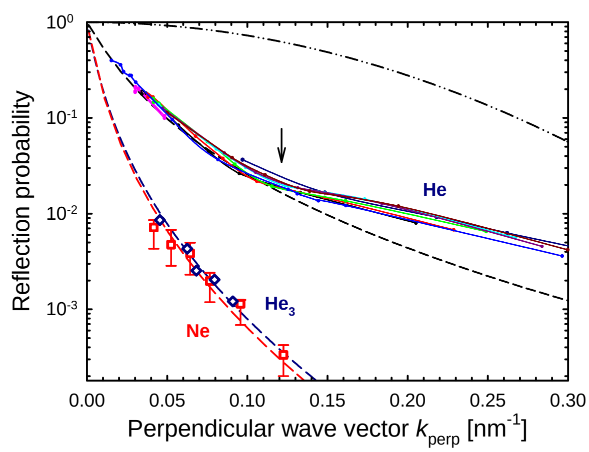

Figure 1: *Coherent reflection probability for He, He$_3$, and Ne. The slope of the observed data (points and solid lines) cannot be explained by a classical surface-reflection model (dash-dotted line), but, for small k_{perp}, it is well reproduced by a 1-dimensional quantum-reflection model (dashed lines).*

Spinor Dynamics in an Antiferromagnetic Condensate

Y. Liu[1,2], S. Jung[2], S. Maxwell[2], L. Turner[2], E. Tiesinga[1,2], P. D. Lett[1,2]

[1] *Joint Quantum Institute, University of Maryland*
[2] *National Institute of Standard and Technology, Gaithersburg, MD 20899*

Spinor condensates of sodium provide an accessible way to study spin population dynamics and domain formation of an antiferromagnetic quantum system. ^{23}Na atoms are condensed in the F = 1 hyperfine state in a tight optical trap, which allows a description with a single spatial wavefunction and an independent 'spinor' wavefunction containing the spin variables. If the spin populations are initiated to a non-equilibrium state, a collisional exchange which couples two m = 0 atoms to one m = +1 and one m = -1 atom takes place, leading to oscillations in the populations. A competition between the collisional interaction and quadratic Zeeman interaction leads to a divergence in the spin oscillation period near a critical magnetic field (or a critical evolution time). In our recent experiments, we use Faraday rotation spectroscopy as a less-destructive method to continuously monitor the population dynamics and demonstrate a sharp signature to determine the critical field (or time) independent of a numerical fitting, which may be applied as a high-precision magnetometer. This study also confirms a strong dependence of the critical magnetic field on magnetization (the difference in population between m = +1 and m = -1), as shown in Figure 1, which only exists in an antiferromagnetic system.

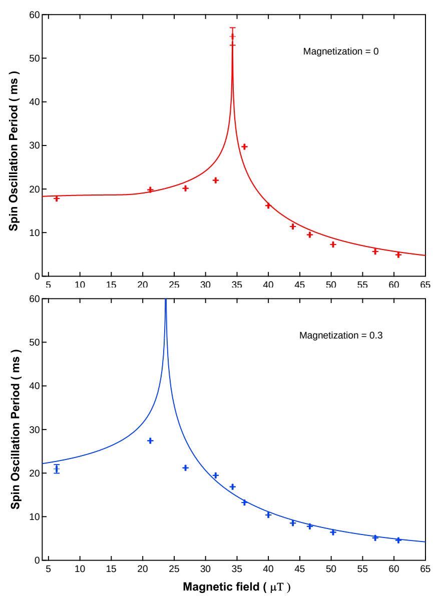

Figure 1: *Period of spin oscillations as a function of applied magnetic field when magnetization is equal to 0 (above) and 0.3 (below). The solid lines and dots are theoretical predictions and experimental data, respectively.*

Investigation of the energy distribution and cooling of a single atom in an optical tweezer

C. Tuchendler, A. M. Lance, A. Browaeys, Y. R. P. Sortais, P. Grangier

Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Univ.Paris-Sud, Campus Polytechnique, RD 128, 91127 Palaiseau Cedex, France

Single neutral atoms trapped in tightly focused sub-micron optical tweezers provide a useful architecture for fundamental quantum atom optics research, for quantum information processing and potentially for quantum computation. The knowledge and control of the energy of a single trapped atom is important for many of these applications. As is the case for ions, it is important to reduce the energy of the trapped atom, to ultimately reach the vibrational ground state of the trapping potential. In the framework of quantum computing, for example, the entanglement of two atoms via controlled collisions usually requires ground state cooling (see e.g. [1]).
In our experiment, we trap single $^{87}\mathrm{Rb}$ atoms in a strongly focused dipole trap that has an optical waist of $w = 1.03 \pm 0.01$ μm and is produced by focusing a ~ 850 nm laser in the center of an optical molasses using a large numerical aperture ($\mathrm{NA} = 0.5$) aspherical lens [2]. A collisional blockade mechanism prevents two or more atoms from being trapped simultaneously due to inelastic collisions[3].
We experimentally investigate the energy distribution of a single atom in the optical tweezer under different cooling regimes[4]. We use two independent methods to measure the temperature of the atom, and show that the energy distribution of the radiatively cooled atom is close to thermal. After laser-cooling, the temperature of the atom is typically 33 μK in a 2.8 mK deep trapping potential. We then demonstrate how to further reduce the energy of the atom, firstly by adiabatic cooling, and secondly by truncating the Boltzmann distribution of the single atom. This provides a non-deterministic way to prepare the atom at low microKelvin temperatures, close to the ground state of the trapping potential. These results provide the right conditions to implement a protocol to entangle two similarly cooled atoms, based on the emission of a single photon by one of these two trapped atoms[5]. These results also place us in a good position to further cool the atom down to the ground state, for example by using Raman sideband cooling.

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Progress on a Helium Slower for MOT Loading using the Bichromatic Force

D. E. Chieda, Bryan Conway, Nicholas Destefano, E. E. Eyler

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

Atomic spectroscopy of helium continues to serve as an important benchmark for fundamental atomic physics. The next generation of high-resolution studies will require cooled and trapped atomic samples to eliminate Doppler and transit-time broadening. Magneto-optical traps (MOTs) for metastable helium are particularly difficult to load, usually requiring Zeeman slowers with a length of 2-3 meters and a high degree of engineering complexity. The bichromatic force offers an alternative method of slowing metastable helium atoms[1] that should allow a significantly simpler and much more compact apparatus.

The bichromatic force utilizes controlled momentum exchange between atoms and widely detuned two-frequency (bichromatic) counterpropagating laser fields. The irradiances are adjusted such that the beat notes from each bichromatic field are π-pulses for the cycling $2\,^3S \rightarrow 2\,^3P$ transition at 1083 nm. A net longitudinal force arises from careful control of the sequence of absorption and stimulated emission from the counterpropagating beams, and can be orders of magnitude greater than the radiative force. The force is non-adiabatic, and can induce cooling as well as slowing. Further, the bichromatic force has a large velocity range that largely eliminates the need for Doppler compensation. Computer modeling indicates that helium atoms can be slowed by a total of 900 m/s by use of two bichromatic stages with detuning of 375 MHz. The total length of the slowing region is only about 10 cm.

We describe progress on an experimental realization of this two-stage slower designed specifically for MOT loading. Metastable helium atoms at $\sim$77 K are produced by a liquid-nitrogen-cooled DC discharge, similar to arrangements used elsewhere for Zeeman slowers. The bichromatic force is implemented using a fiber-amplified diode laser, which is split and frequency-shifted by a configuration of three acousto-optic modulators to produce the four bichromatic beams needed for a two-stage slower. A mechanical chopper is used to allow accurate velocity profiling of the metastable beam. The slower is designed for a final longitudinal velocity of about 80-100 m/s, with a small transverse component to facilitate loading into a separate MOT chamber.

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A new BEC experiment at the University of Cambridge

S. Palzer, C. Zipkes, C. Sias, M. Köhl

Cavendish Laboratory, University of Cambridge, JJ Thomson Av., Cambridge CB3-0HE, United Kingdom

We present a new experiment realizing Bose-Einstein condensation in a dilute gas that is under construction at the University of Cambridge. The first step in order to obtain a BEC is the collection of $\sim 10^9$ ^{87}Rb atoms in a Magneto Optical Trap (MOT). The cloud is then magnetically transferred for 132mm in a second chamber where ultra high vacuum is realized. There, the atoms are trapped in a QUIC trap, and the BEC is then realized by radiofrequency-assisted evaporative cooling. The vacuum system has been designed to facilitate very good optical access and - in the long term - an ion trap to study collisions between cold atoms and cold ions. The poster presents an overview over the current status of the experiment.

Resonance fluorescence spectrum of a single neutral trapped atom in strong Lamb-Dicke regime

W. Kim, Y. Choi, S. Kang, S. Lim, J.-H. Lee, K. An

Department of Physics and Astronomy, Seoul National University, Seoul, 151-747, Korea

For weakly excited two-level atoms localized in a sub-wavelength region (Lamb-Dicke regime), the resonance fluorescence exhibits not only Dicke narrowing but also vibrational Raman sidebands. We have measured the resonance fluorescence spectrum of a small number of rubidium atoms trapped in micro-potentials formed in a phase-stabilized magneto-optical trap[1] by using the photon-counting second-order correlation spectroscopy [2]. In our experiment, the second-order correlation function $g_h^{(2)}(\tau)$ of the heterodyne signal formed by resonance fluorescence from a few atoms and a weak local oscillator was first measured by photon counting and then the first-order coherence of the resonance fluorescence contained in $g_h^{(2)}(\tau)$ was Fourier-transformed to reveal the resonance fluorescence spectrum. The resulting spectrum shows a narrow central peak and small sidebands corresponding to Dicke narrowing and vibrational Raman sidebands, respectively. From the measured spectra, various information about trapped atoms such as temperature, atomic population in vibrational levels and harmonic oscillation frequency in the micro-potential were obtained. Combined with our atom-number feedback technique[3], by which the number of trapped atoms was precisely controlled, we could measure the resonance fluorescence spectrum of a single rubidium atom localized in a micro-potential.

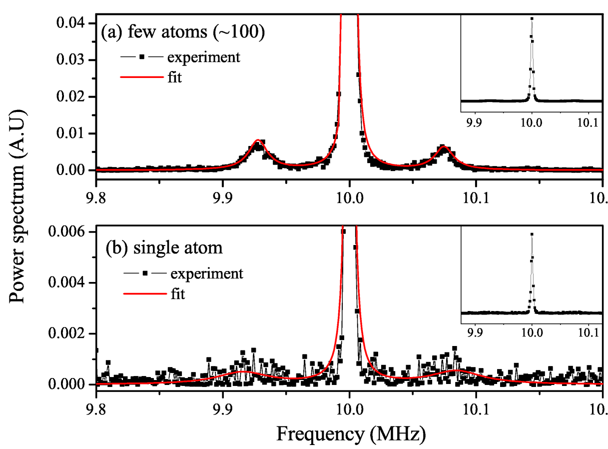

Figure 1: *Resonance fluorescence spectrum of (a) a few atoms and (b) a single atom measured by the photon-counting second-order correlation spectroscopy.*

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Cavity cooling of ^{88}Sr^{+}

D. R. Leibrandt, J. Labaziewicz, I. L. Chuang

Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Cavity cooling is a method of laser cooling which uses coherent scattering into an optical cavity to cool particles.[1] The particle to be cooled is placed in an optical cavity and excited with a laser tuned to the red of a cavity resonance. On average, scattering events which remove a photon from the laser and put it into the optical cavity cool the particle. The cooling limit is determined by the linewidth and cooperativity of the cavity, which can be designed to allow sub-Doppler cooling. Furthermore, because the cooling limit is independent of the energy level structure of the particle, cavity cooling is in principle applicable to particles without closed optical transitions.[2]

In this work we describe an experiment to study three-dimensional cavity cooling of a single ^{88}Sr^{+} ion in the previously unexplored resolved sideband regime. The ion is confined in a linear RF Paul trap with frequencies of $2\pi \times (0.86, 1.2, 1.5)$ MHz. Large cavity cooling rates are attained by cooling near the 422 nm $S_{1/2} \leftrightarrow P_{1/2}$ optical dipole transition. We use a 5 cm long, near-confocal Fabry-Pérot cavity with a linewidth of $2\pi \times 86$ kHz and a cooperativity of 0.088. The theoretical cavity cooling limit is 2 motional quanta, which is less than the Doppler cooling limit for ^{88}Sr^{+} on the $S_{1/2} \leftrightarrow P_{1/2}$ transition. We present details of the experimental implementation and preliminary results.

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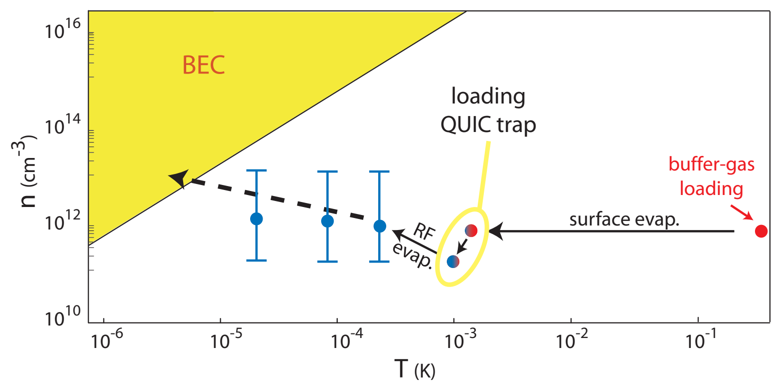
Progress towards a buffer gas cooled BEC of metastable He

S. C. Doret[1,3], C. B. Connolly[1,3], W. Ketterle[2,3], J. M. Doyle[1,3]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2]*Department of Physics, MIT, Cambridge, MA 02139, USA*
[3]*Harvard-MIT Center for Ultracold Atoms, Cambridge, MA 02139, USA*

We report recent progress towards producing a BEC of metastable helium (^{4}He*) using buffer gas cooling. 10^{11} ^{4}He* atoms are produced via RF-discharge and magnetically trapped at an initial temperature of 400 mK in an anit-helmholtz quadrupole field. These atoms are evaporatively cooled to the ultracold regime via surface evaporation [1] [2] and transferred to a superconducting QUIC trap [3] with trap frequencies of $\omega_{\mathrm{axial}} = 2\pi \times 200$ Hz and $\omega_{\mathrm{radial}} = 2\pi \times 2000$ Hz, resulting in a cloud of $\sim 10^9$ atoms at a temperature of 1 mK. Magnet currents are post-stabilized to the 10^{-5} level. Trap lifetimes well in excess of 300 seconds are observed, limited only by collisions with residual background gas. Further cooling to temperatures below 10 μK is achieved via RF evaporation, and the cloud is detected via absorption or phase contrast imaging at either 1083 nm or 390 nm.



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Cold electron beams from trapped atoms

G. Taban, M. P. Reijnders, B. Fleskens, S. B. van der Geer, O. J. Luiten, E. J. D. Vredenbregt

Department of Applied Physics, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Netherlands

In the quest for higher brightness electron beams, there are at least two distinct pathways that are being pursued. One is the reduction of the source size, leading to the development of needle and nanotube sources [1]. The other, pursued by us [2] [3], is the reduction of the beam divergence by decreasing the random thermal motion of the electrons.
To achieve this, we start from a cloud of trapped rubidium atoms, located inside a coaxial accelerating structure [4]. The atoms are then either photo-ionized in a DC electric field by a pulsed laser that is tuned near the ionization threshold, or field-ionized by a pulsed electric field after excitation to a high Rydberg state. The resulting transverse temperature of the extracted electrons is deduced from the dependence of the spatial size of the electron-optical image of the electron pulse on the beam energy, measured using an MCP+phosphor assembly. The electric fields inside the accelerator are accurately known from an electro-optical measurement as well from ion time-of-flight measurements.
With DC fields, analysis of the detector images obtained yields electron temperatures as low as 15K, with an expected linear dependence on the ionization laser wavelength further above threshold. With pulsed fields, we use various Rydberg states to observe the dependence of image size on beam energy, and obtain similar results. We also calculate the expected transverse temperature by a quantum-mechanical solution of the excited hydrogen problem in DC electric fields. These calculations yield temperatures in the same regime as the experimental observations but are not in full agreement.
The low temperatures achieved experimentally illustrate the potential of the source for e.g. ultrafast electron diffraction experiments where a coherence length of several nm may be achievable.

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Solid-state laser source at 589 nm for laser cooling of Sodium

E. Mimoun, L. De Sarlo, J. Dalibard, F. Gerbier

Laboratoire Kastler Brossel, ENS, Université Pierre et Marie-Curie-Paris 6, CNRS, 24 rue Lhomond, 75005 Paris, France

A Bose-Einstein condensate is a natural candidate when it comes to studying quantum interactions between atoms. Among the many atomic species that can be brought to quantum degeneracy, Sodium benefits from low inelastic losses and a relatively large elastic cross-section. Such qualities are critical to reduce decoherence due to atom losses, and eventually observe squeezed atomic states or even macroscopic quantum superpositions for small ensembles. In addition, they are of key importance to use sodium as a buffer gas for sympathetically cool fermionic species to quantum degeneracy[1].

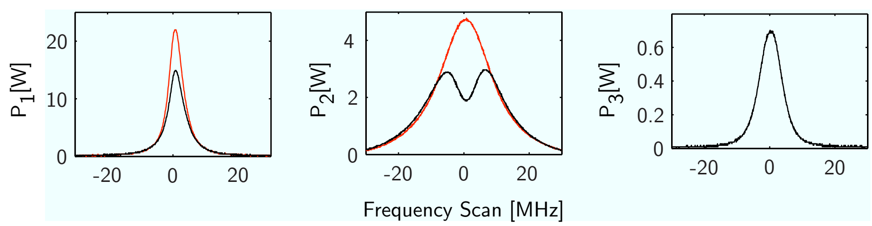

Figure 1: *Intra-cavity SFG : Lasers 1 (1064 nm) and 2 (1319 nm) are enhanced in an optical cavity. When simultaneously resonant they produce a laser noted 3 at 589 nm. Powers for the three lasers are plotted while the length of the cavity is scanned. The depletion of lasers 1 and 2 changes the shape of the line for laser 2, hence cavity-locking adjustments are needed.*

In spite of these advantages, experiments with sodium atoms are comparatively rare due to the necessity of working with dye lasers, which are difficult to maintain and operate, in order to access the laser cooling line at 589 nm. In this work we report on a solid state laser source at 589 nm, using sum frequency generation (SFG) in a PPKTP non-linear crystal. The crystal is enclosed in an optical cavity, designed to enhance the non linear conversion process. While high intra-cavity efficiencies bring cavity-locking problems (see Fig. 1), these have been overcome electronically. It was then possible to reach powers as high as 800 mW of single mode laser light at 589 nm, out of 1.2 W at 1064 nm and 500 mW at 1319 nm, the two latter sources being monolithic YAG lasers. This corresponds to converting 92% of the incoming photons at 1319 nm coupled into the cavity. We therefore believe this constitutes an efficient and cost-effective alternative to dye lasers to cool sodium atoms.

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Superconducting atom-chip for groundstate and Rydberg atoms

A. Emmert[1], A. Lupascu[1], C. Roux[1], T. Nirrengarten[1], G. Nogues[1], M. Brune[1], J.-M. Raimond[1], S. Haroche[1,2]

[1]*Laboratoire Kastler Brossel, ENS-CNRS-UPMC, 24 rue Lhomond, 75005 Paris, France*
[2]*Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France*

Atom-chips allow an accurate control of the external degrees of freedom of magnetically trapped atoms due to very high field gradients with moderate currents. Therefore, the miniaturization and integration of cold atom experiments are possible. Moreover, complex trapping potentials are realizable with state of the art nanofabrication techniques.

At small distances from the metal chip surface ($< 10\ \mu$m), the lifetime of trapped atoms is reduced by magnetic near field fluctuations. The latter are caused by thermally induced current fluctuations in the non-zero resistance chip wires (fluctuation-dissipation theorem).
Theoretical predictions show that at cryogenic temperatures (4 K) and above a superconducting slab, the lifetime is several orders of magnitude longer than in front of a regular metal at the same temperature [1]. We have shown that this remains true even in the presence of vortices in the superconducting material [2].

Moreover, cryogenic temperatures allow coupling of atoms to macroscopic quantum devices like micromechanical resonators, Squids or superconducting planar cavities with low population of thermal phonons/photons. To enhance the coupling to these devices, highly excited atoms (Rydberg atoms) with huge dipole moments ($> 1000\ e \cdot a_0$) could be used in a negligible blackbody radiation background essential for the preservation of these atomic states [3].

We present in this context the first realization of a magnetic trap [4] and the production of a Bose-Einstein condensate on a superconducting atom-chip [5]. Long trapping lifetime (115s) is achieved far from the chip and we observe the onset of Bose-Einstein condensation for $1 \cdot 10^4$ atoms at 100 nK.

Numerical calculations show that the preparation of a single Rydberg atom on demand by dipole blockade mechanism [6] should be possible with our present setup.

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Imaging magnetic fields using velocity selective resonances in cold atom clouds

M. L. Terraciano, M. Bashkansky, Z. Dutton, F. K. Fatemi

Optical Sciences Division, Naval Research Laboratory, Washington, DC 20375

We describe and demonstrate a simple technique for single-shot magnetic field imaging using stimulated Raman transitions. Cold atoms released from a magneto-optical trap (MOT) are exposed to a brief (1 ms) counterpropagating laser pulse in a lin-perp-lin configuration detuned a few GHz from resonance. Raman transitions in this configuration couple different magnetic sublevels with well-defined velocity. Because the two-photon resonance condition is satisfied only for narrow velocity classes, most atoms continue freely expanding. However, resonant atoms are kicked by two photon momenta. Therefore, because an image of the expanded cloud is a mapping of the atom cloud momentum distribution, the narrow resonant velocity classes appear as distinct, well-defined features on an otherwise smooth fluorescence image.
The participating energy levels are Zeeman shifted in a magnetic field, resulting in field-dependent velocity classes. When the Raman pulse is applied to an atom cloud with finite size, magnetic field variations across the sample result in position-dependent features in images of the expanded cloud (see Fig. 1). This technique has proven useful in our lab for compensating ambient magnetic fields.[1] The technique is easily implemented in existing cold atom setups, because the MOT repump beam can also serve as the Raman beam.

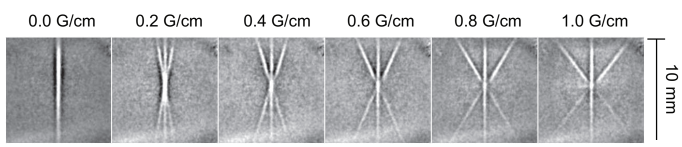

Figure 1: *Images of the expanded atom cloud, after background subtraction, for several magnetic field gradient values.*

When the stimulated Raman transitions occur between different hyperfine ground states, which have opposite Zeeman shifts, the resonance condition is dependent on the initial magnetic sublevel quantum number. We have used this technique for single-shot imaging of magnetic sublevel distributions. To demonstrate this idea, we have monitored the evolution of sublevel distributions when the sample is exposed to optical pumping pulses of different durations.

[1] M. L. Terraciano, S. E. Olson, M. Bashkansky, Z. Dutton, and F. K. Fatemi, Phys. Rev. A **76**, 053421(2007)

Towards sympathetic cooling of a Bose-Fermi mixture

G. Smirne, G. D. Bruce, L. Torralbo-Campo, V. C. Chan, D. Cassettari

School of Physics and Astronomy, University of St. Andrews. North Haugh, St Andrews, FIFE, KY16 9SS, United Kingdom

The poster illustrates our progress so far and the future plans towards the construction of an experimental setup for the production of quantum degenerate Bose-Fermi mixtures. Our system, which at present comprises a vapor-loaded ^{87}Rb MOT, will include shortly a ^{6}Li MOT as well, and an optical trap in which the two species will be brought to quantum degeneracy by evaporative cooling of the bosonic component, which in turn will sympathetically cool also the fermionic gas.

The quantum degenerate mixture, or the Fermi gas alone, will be loaded into an optical lattice in order to study respectively the formation of heteronuclear molecules and the anti-ferromagnetic phase of the Fermi gas in the lattice. Spatial light modulators are planned to be used to generate our optical potentials, and this will also open the possibility of forming irregular pattern of dipole traps to create trapping geometries not achievable using standard techniques[1]. The irregularity of the pattern is an interesting feature because it removes, from the observed collective properties of the optically trapped atoms, features that are due to the periodicity of the lattice. The SLM is an inherently dynamic tool that will also offer the opportunity to control the ratio of the tunneling between traps to the interaction strength within an individual trap, thus providing full coherent control over the gas interactions.

We are currently setting up a system to enhance the loading of atoms in our MOT from background vapor by the addition of a slower beam directed towards the arm of the vacuum chamber housing the getter source. This technique is hoped to be used to allow also the loading of Lithium atoms without employing a Zeeman slower. We aim to having tested light-induced atomic desorption (LIAD) for loading our Rb MOT before the Conference, and show results from this investigation. The pulsed operation of the getter source is also going to be explored and compared to the results obtained with the LIAD. These techniques will be tried also for Lithium, and if successful they will allow us to achieve low background pressure in our MOT chamber, ready for evaporative cooling in the optical trap.

[1] V. Boyer, R. M. Godun, G. Smirne, et.al., Dynamic Manipulation of Bose-Einstein Condensates With a Spatial Light Modulator, Phys. Rev. A **73**, 031402(R) (2006).

Entropy Exchange in Laser Cooling*

Harold Metcalf

Physics and Astronomy, Stony Brook University, Stony Brook NY 11794-3800 USA

It is a long-standing and widely held tenet in the laser cooling community that spontaneous emission (SpE) is required to carry away the entropy lost by a vapor of atoms being cooled. In this poster I suggest that SpE is not the only way of removing the entropy, and that the laser fields themselves are capable of absorbing it. That is, the changes in the laser beams themselves results in a sufficiently large reservoir of N different states accessible to the system that their entropy $S = k_B \ln N$ is sufficient to absorb the entropy lost by the atoms in the cooling process. This is done by comparing the entropy lost by the cooled atoms with the entropy capacity of the laser fields. This description requires that the light field be included as part of the system, and not just as an externally applied potential. Proper choice of laser parameters could possibly produce cooling of atoms or molecules over a wide range of temperatures without SpE.

Laser cooling is usually viewed as velocity space compression by a velocity dependent optical force. Since such forces do not conserve energy, their full description must include the energy added to the light field at a frequency above that of the laser beams, usually by SpE. Thus the fluorescent light field, as well as the cooling laser beams, must be part of the system under consideration. Moreover, it is usually presumed that SpE is necessary to remove the entropy lost by the atoms. A closer look suggests that SpE does this by redistributing the light among the multitude of empty states of the radiation field. Here it is shown that it can equally well be done by stimulated emission into laser beams themselves.

Although the natural choice for a description of the light beams might seem to be the familiar coherent states $|\alpha\rangle$, the usual description of $|\alpha\rangle$'s is not well-suited to the exchange of light between beams caused by absorption-stimulated emission cycles of atoms. Care must be taken when describing these beams as coherent states, and one must be cautious when applying the annihilation operator a to a coherent state $|\alpha\rangle$. In particular, the transition term of the Jaynes-Cummings Hamiltonian is $(ab^\dagger + a^\dagger b)$, and although $|\alpha\rangle$ is an eigenstate of a, $a^\dagger|\alpha\rangle$ is a complicated object. Moreover, the $|\alpha\rangle$'s are not eigenstates of the Hamiltonian $\hbar\omega(a^\dagger a + 1/2)$ nor are they orthogonal. Still, they represent a suitable approximation as long as it's recognized that atomic absorption indeed does change the actual state of a real field, even though in the exact (ideal) case, $|\alpha\rangle$ is an eigenstate of a.

The coherent entropy exchange between the atoms and the laser fields does NOT constitute a loss of entropy, but merely its redistribution among parts of the system. Thus it doesn't violate the Liouville theorem or unitarity because neither the total entropy nor the system's phase space volume is reduced, but merely exchanged between its parts. The entropy in the light field is not dissipated until the outgoing beams hit the walls in a nonconservative, irreversible process. The walls are not part of the system, just as the empty modes into which SpE dumps the light are not part of the usual description of optical molasses.

*Supported by ONR

Neutral Atom Lithography Using a Bright Metastable Helium Beam*

Claire Shean, Jason Reeves, Harold Metcalf

Physics and Astronomy, Stony Brook University, Stony Brook NY 11794-3800 USA

We have performed neutral atom lithography using a bright beam of metastable Helium (He*). He* is collimated out of a reverse flow DC discharge source [1]. with the bichromatic force followed by two optical molasses velocity compression stages. The resulting beam has a divergence of 2.3 mrad and current of 3×10^8 atoms/s through aperture of 0.1 mm^2. We have previously demonstrated this lithography method using a metal grid with a 12 μm periodicity to project its image on a self assembled monolayer (SAM) of nonanethiol. The open areas of the grid allow incident He* to damage the SAM molecules by depositing their 20 eV of internal energy on the surface. The undisturbed SAM then protects a 200 $\mathring{A}$ layer of gold that has been evaporated onto a prepared Silicon wafer from a wet chemical etch [2]. Samples created with this method have an edge resolution of 63nm that was observed using an atomic force microscope. The edge resolution appears to be limited by our current wafer preparation and processing methods.

We have now achieved focusing of the He* beam into lines as shown at the right by the dipole force the atoms experience while traversing a standing wave of λ = 1083 nm light tuned 500 MHz above the $2^3S_1 \rightarrow 2^3P_2$ transition. The lines are separated by $\lambda/2$ and their length is comparable to the laser beam waist. This is a parallel fabrication technique that creates structures whose spacing is accurate over large distances with a 10^{-5} estimated relative uncertainty[3]. Because bichromatic collimation makes such an intense He* beam, our exposure time is measured in minutes instead of hours.

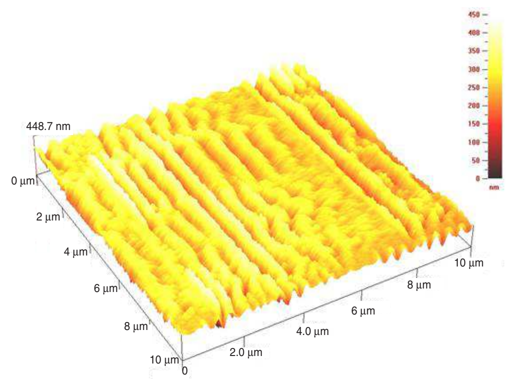

Figure 1: *An AFM scan of an etched wafer whose lines are spaced by ≈530 nm. Within the calibration accuracy of the AFM, this is $\lambda/2$ of the 1083 nm wavelength of the $2^3S_1 \rightarrow 2^3P_2$ transition. The wiggles are artifacts of the AFM scan.*

* Supported by ONR and Dept. of Education.

[1] J. Kawanaka, MaHagiuda, K Shimizu, F, Shimizu, H Takuma; Appl. Phys. B **56**, 21-24 (1993)
[2] Y. Xia, X. Zhao, E. Kim, G. Whitesides; ChemMater 7, 2332-2337 (1995).
[3] J. J. McClelland, W.R. Anderson, C. C. Bradley, M. Walkiewicz, R. J. Celotta; J.Res.Natl.Inst.Stand.Technol 108, 99-113 (2003).

Infrared Spectroscopy of Magneto-optically Trapped Calcium Atoms

I. Norris, U. Dammalapati, M. Borkowski A. S. Arnold, E. Riis

Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK

The energy level structure of the alkali-earth atoms presents laser cooling with a range of challenges and opportunities compared with the more familiar alkali metals. The two outer electrons result in a singlet ground state with a strong cooling transition while narrow inter-combination lines connect to the triplet scheme. Linewidths in the kHz range and below for the ${}^1S_0$-${}^3P_1$ line offer the tantalising prospect of extremely low Doppler temperatures and hence laser cooling all the way to BEC[1]. BEC has been achieved in the similar Yb system[2], but so far not with alkali-earths.
We report on the development of an experiment using laser cooled calcium. The ${}^1S_0$-${}^1P_1$ cooling transition is at 423 nm and in excess of 100 mW of light at this wavelength is generated using a frequency doubled Ti:Sapphire system. Atoms from a Zeeman slowed thermal beam are deflected into a custom built magneto-optical trapping chamber using 2D optical molasses. Initial demonstrations show that we magneto-optically trap in excess of a million ${}^{40}Ca$ atoms without the use of any re-pumping laser. The main loss mechanism is a decay into the triplet scheme which can be intercepted by a laser at 672 nm resulting in quadrupling of the atom number. The temperature of the atoms is in the 2-3 mK range. We report on the observation of the ${}^1D_2$-${}^3P_2$ transition at 1530.5 nm, previously unseen in calcium. This transition could be used as an efficient way to drive atoms lost from the main cooling transition back to the ground state.

[1] C.S. Adams, *et al*, "Laser cooling of calcium in a 'golden ratio' quasi-electrostatic lattice", J. Phys. B **36**, 1933 (2003)

[2] Y. Takasu, *et al*, "Spin-singlet Bose-Einstein condensation of two-electron atoms", Phys. Rev. Lett. **91**, 040404 (2003)

Theoretical analysis of trapped atom interferometers using laser cooled sources

James A. Stickney[1], James Scoville[2], Matthew B. Squires[2], Paul Baker[2], Steven M. Miller[2]

[1]*Space Dynamics Laboratory, Bedford, MA 01730, USA*
[2]*Air Force Research Labortory Hanscom AFB, MA 01731, USA*

To dramatically increase the sensitivity of an atom interferometer, without increasing the overall size of the device, the atoms must be held up against gravity and confined to prevent dispersion of the atomic gas. Laser cooled atomic gasses are a viable alternative to BEC sources in atom interferometry in applications where wave-packet separation is not necessary. Interferometers that use laser cooled sources have several advantages over BEC including a lower atomic density, which results in smaller mean-field effects. They are also less sensitive to small perturbations in the potential. We present a theoretical analysis of an atom interferometer that uses laser cooled sources. Decoherence due to both the confining potential and atom-atom interactions will be analyzed.

Light-shift tomography in an optical-dipole trap

J-F. Clément, J-P. Brantut, M. Robert de St Vincent G. Varoquaux, R. A. Nyman, A. Aspect, T. Bourdel, P. Bouyer

Laboratoire Charles Fabry de l'Institut d'Optique, Campus Polytechnique, RD 128, 91127 Palaiseau, France

We report on light-shift tomography of a cloud of ^{87}Rb in a far-detuned optical-dipole trap. At this wavelength, the excited state of the cooling transition of ^{87}Rb is strongly red-shifted, which enables us to perform energy-resolved imaging. We take advantage of this specific feature by using it in two different situations.

(i) *Mapping of the optical potential*. Starting with a cold cloud with a smooth density profile, we switch on a trapping laser at 1565 nm, and immediately take an absorption image of the atoms in the presence of the trap (before any evolution of the cloud density due to the trapping effects). By scanning the probe laser frequency, we perform a mapping of the equal light-shift regions, i.e. tomography of the trap potential.

(ii) *Measurement of the atomic potential energy distribution*. By counting the total number of atoms detected at a given probe detuning, we directly measure the atomic potential energy distribution of the cloud, i.e. the number of atoms having a given potential energy in the trap. We follow the evolution of this distribution for a trapped cloud during the free-evaporation process, starting from a strongly out-of-equilibrium situation and relaxing towards a thermal distribution. We then conclude on possible applications of light-shift tomography with ultracold atoms.

Using a spatially-varying light field, this technique could be used to adress atoms situated in regions which size is smaller than the laser wavelength.

Hyperfine Pumping Resonance for Sub-Doppler Cooling in ^{87}Rb

Krishna Myneni

U.S. Army RDECOM, AMSRD-AMR-WS-ST, Redstone Arsenal, AL 35898

We demonstrated a technique which may be used to lock a laser at an optical frequency suitable for achieving sub-Doppler temperatures in ^{87}Rb atoms. The cooling laser may be detuned and fixed precisely at an optical frequency of $\Delta = -6\Gamma$ from the cooling transition ($5S_{1/2}\ F = 2 \rightarrow 5P_{3/2}\ F' = 3$), without the use of an AOM. Only the addition of a simple pump-probe configuration in an external Rb vapor cell is needed. A resonance is created at the fixed detuning by optical hyperfine pumping in the external vapor cell. With the repumping laser locked to the $F = 1 \rightarrow F' = 0, 1$ crossover resonance, via a saturated-absorption spectrometer, a specific velocity group of atoms in the vapor cell is optically pumped into the lower level of the cooling transition via the $F = 1 \rightarrow F' = 1 \rightarrow F = 2$ path. Only a minute fraction of the cooling laser power is required to be split off to the vapor cell, to serve as the probe beam. As the cooling laser (probe) is swept in frequency, the detector output shows a resonance in its absorption spectrum at $\Delta/2\pi = -36$ MHz (-6Γ). This resonance, shown in Figure 1, is due to the hyperfine pumping induced by the repumping laser, and occurs at a detuning set by half the spacing between the upper $F' = 0$ and $F' = 1$ hyperfine levels of the atom. By locking to this resonance, the cooling laser frequency may be fixed to achieve sub-Doppler temperatures in optical molasses or in a magneto-optical trap. Our technique can reduce the optical power requirement for a cooling laser, and may simplify standard frequency shifting and locking techniques used in portable cold-atom based technologies, such as quantum inertial sensors.

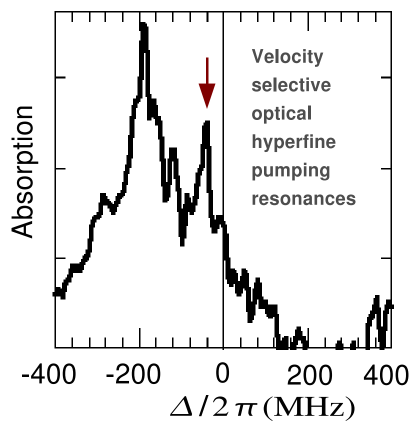

Figure 1: *the arrow marks the hyperfine resonance at* $\Delta = -6\Gamma$

Trapped-Atom Cooling Beyond The Lamb-Dicke Limit Using Electromagnetically-Induced Transparency

M. Roghani, H. Helm

University of Freiburg, D-79104 Freiburg, Germany

We investigate the cooling of trapped atoms by Electromagnetically-Induced Transparency (EIT) under conditions of weak confinement and beyond the Lamb-Dicke limit, i.e. the spontaneous decay width is large compared to the trap oscillation frequency and the recoil energy is a substantial fraction of the vibrational energy spacing of the trap. Morigi *et al.* [1] have shown, by applying two laser beams to the trapped atomic sample in a way that EIT conditions are satisfied, there is the possibility to cool ions to the ground state of a trap. This scheme proves highly efficient in case of cooling ions in tight traps when the condition of small Lamb-Dicke parameter and the condition of spontaneous emission rate smaller than trap frequency can be met. Transferring this scheme to typical cases of neutral atoms trapped in optical dipole trap environments neither of these conditions can be stringently met. In the neutral atom case typical values of the Lamb-Dicke parameter are in the range of 0.2-1 and spontaneous emission rates are much greater than the trap frequency. We have explored this situation by developing the Liouville equation for a density matrix describing entangled states of the vibrational and electronic motion by taking into account the modification of the EIT line-shape due to vibrationally off-diagonal transitions in emission and absorption.

Our numerical solutions of the Liouville equation for a density matrix describing states of vibrational <u>and</u> electronic degrees of freedom show that vibrational cooling is feasible at even substantial values of the Lamb-Dicke parameter and under conditions of weak confinement, a situation where sideband pumping is inefficient. A first report on this subject has just appeared in print [2].

We have also investigated the time-dependent Wigner function of trapped-atom states in order to study the temporal behavior of the atom(s) in phase space under EIT-cooling conditions. The nonlinear coherent superposition of trap states reveals highly interesting and novel features. Among these is the initial displacement of the atom’s position due to momentum transfer in stimulated absorption and stimulated emission. This phase is followed by slow equilibration of the atom to the trap center due to spontaneous emission. The importance of the recoil energy, the Lamb-Dicke, and trap parameters in this process is investigated.

[1] F. Schmidt-Kaler, J. Eschner, G. Morigi, C. F. Roos, D. Leibfried , A. Mundt, and R. Blatt, Applied Physics B **73**, 807 (2001)

[2] M. Roghani and H. Helm, *Trapped-Atom Cooling Beyond The Lamb-Dicke Limit Using Electromagnetically-Induced Transparency*, Physical Review A, **77**, 043418 (2008)

Multichamber vacuum system for atom interferometry

Matthew B. Squires[1], James Scoville[1], Paul Baker[1], James A. Stickney[2], Steven M. Miller[1]

[1]*Air Force Research Labortory Hanscom AFB, MA 01731, USA*
[2]*Space Dynamics Laboratory, Bedford, MA 01730, USA*

Atom interferometry has shown great potential as the basis for highly sensitive accelerometers and gyroscopes. Compared to optical interferometers and gyroscopes atom interferometry is limited by signal to noise due to small atom number ($< 10^6$) and low duty cycle (< 10 Hz). We propose a multichamber vacuum system to increase the duty cycle of atom interferometry sensors. The first chamber operates a 2D magneto-optical trap (MOT) to provide a high flux source of cold atoms. A 3D MOT in the second chamber collects atoms from the 2D MOT and provides additional laser cooling and optical pumping for magnetic trapping. After the atoms are magnetically trapped they are transported from the second chamber to the third chamber though a light baffle to optically isolate the third chamber from scattered resonant light. The third chamber will be used for atom interferometry using both laser cooled atoms and BEC.

Intense Cold Atom Source

M. Borysow, T. C. Briles, B. L. Stoll, D. J. Heinzen

Department of Physics, University of Texas at Austin, Austin, TX 78712

We are developing an intense cold atom source based on continuous post-nozzle injection of Li atoms into a supersonic helium jet. The jet will operate at a temperature of 5 Kelvin and with a flux of 10^{20} helium atoms per second, corresponding to a helium phase space density of order 10^{-3}. By adiabatic expansion, the temperature in the moving frame will be reduced into the mK regime. Li atoms injected into the beam will become entrained in the helium flow, and subsequently extracted from it with a magnetic lens. Numerical simulations show that high efficiency of capture and extraction may simultaneously be realized. We anticipate that the extracted Li beam will have a brightness that is substantially larger than what can be achieved with laser-cooling. However, the brightness of the extracted Li beam could be further enhanced with supplementary laser-cooling. A possible application of this source is a pump for an atom laser.

In this poster, we will present the details of our design and theoretical predictions. The design includes a novel helium jet source and sorption pump, thermally shielded Li source, and magnetic lens. We will also report on our experimental progress in testing these components.

High power second harmonic generation of 514.5 nm light in PPMgLN

M. G. Pullen, J. J. Chapman, D. Kielpinski

Center for Quantum Dynamics, Griffith University, Brisbane, Australia

We report the results of the second harmonic generation (SHG) of green light in a magnesium doped periodically poled lithium niobate (PPMgLN) crystal [1]. Greater than 2 W of stable green light at a maximum efficiency of 32 % was generated by frequency doubling an all fibre light source in single pass configuration. The master oscillator is a single-frequency fibre laser operating at 1030 nm. This is input into a fibre amplifier which provides a linearly polarised output with a maximum power of 10 W at 1030 nm. The output of the amplifier was focused into the crystal and a maximum output power of 2.3 W was observed at 514.5 nm.
The generated light is to be used in the construction of a dipole trap designed to confine Hydrogen atoms. This requires the future construction of an in-vacuum resonant cavity to enhance the green power. This work will be utilised in our attempt to laser cooling Hydrogen using mode-locked lasers as suggested [2].

[1] M. G. Pullen, J. J. Chapman and D. Kielpinksi, "Efficient generation of >2 W of green light by single pass frequency doubling in PPMgLN.", Appl. Phys. 47(10):1397-1400, 2008

[2] D. Kielpinksi, "Laser cooling of atoms and molecules with ultrafast pulses.", Phys. Rev. A, 73(063407):1-6, 2006

Comparison of laser cooling and trapping of even and odd calcium isotopes

A. K. Mollema, R. Hoekstra

KVI Atomic Physics, Universtity of Groningen,
Zernikelaan 25, 9747 AA Groningen, The Netherlands

The trap dynamics of even and odd isotopes of Ca in a magneto-optical trap (MOT) have been investigated. Light alkaline-earth isotopes like ^{40}Ca and ^{88}Sr can be laser cooled and trapped using the optical $^1S_0 -^1 P_1$ resonance transition. Since these transitions are almost closed, both isotopes resemble an almost perfect two-level system. Remarkably enough, measurements yield temperatures that are systematically well above the Doppler temperature limit. However, measurements of the temperature of ^{87}Sr yield temperatures below the Doppler limit[1], which is due to the hyperfine structure of ^{87}Sr. In contrast to the even isotopes the odd alkaline-earth isotopes do have a (non-zero) nuclear spin. Such a sub-Doppler cooling effect might also be expected in the case of ^{43}Ca. We therefore measured the temperature of ^{43}Ca in the MOT of our setup[2] using the release and recapture method and compared this to a similar measurement of ^{42}Ca. Results of the measurements are shown in Fig 1. It turns out that no appreciable sub-Doppler cooling effect is observable in these measurements. It is not yet clear what causes the difference in trapping behavior between ^{43}Ca and ^{87}Sr, however it seems that the exact hyperfine structure details inhibit significant sub-Doppler cooling for ^{43}Ca.

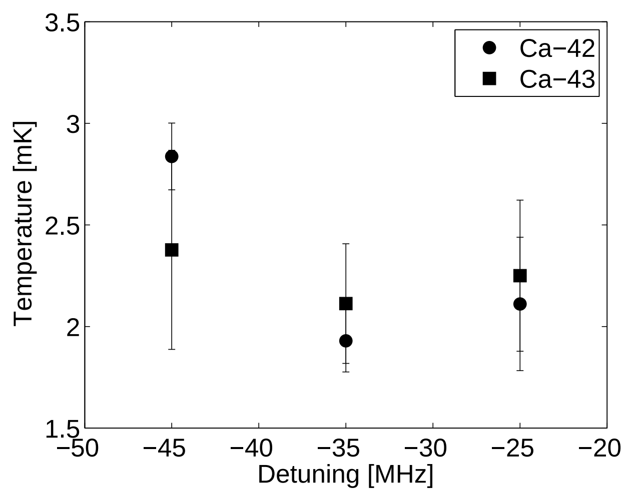

Figure 1: *Results of temperature measurements of* ^{43}*Ca and* ^{42}*Ca in a MOT at low (*$s_0 = 0.1$*) laser intensity.*

[1] X. Y. Xu et al., Phys. Rev. Lett. **90** 193002 (2003)
[2] S. Hoekstra et al., Phys Rev. A **71** 023409 (2005) and A. K. Mollema et al., Phys Rev. A **77** 043409 (2008)

Low energy-spread ion beams from a trapped atomic gas

M. P. Reijnders, P. A. van Kruisbergen, G. Taban, P. H. A Mutsaers, E. J. D. Vredenbregt, O. J. Luiten

Department of Applied Physics, Eindhoven University of Technology, P.O Box 513, 5600 MB Eindhoven, The Netherlands

Pulsed and continuous ion beams are used in applications, such as focussed ion beams. The smallest achievable spot size in focused ion beam technology, is limited by the monochromaticity of the ion source. Here we present energy spread measurements on a new source concept, the ultracold ion source. It produces ion beams by near-threshold ionization of laser cooled atoms. A recent detailed study using realistic particle tracking simulations showed it can compete with the brightness of the industry standard liquid metal ion source (LMI) at reduced longitudinal energy spread [1].

In the experiment Rubidium atoms are captured in a magneto optical trap (MOT) inside an accelerator structure where they are ionized by a pulsed laser in a DC electric field. The resulting cold ion bunch is accelerated towards a multi channel plate detector where the time-dependent ion current is measured. The relative spread in time of flight to the detector is a good measure for the relative longitudinal energy spread in the bunch. Two orders of magnitude lower energy spread is observed than in the current existing ion sources, such as the industry standard liquid-metal ion source. Bunches with an energy of only 5 eV are routinely produced with an rms energy spread as low as 0.02 eV. This proves the feasibility of this new ion source concept.

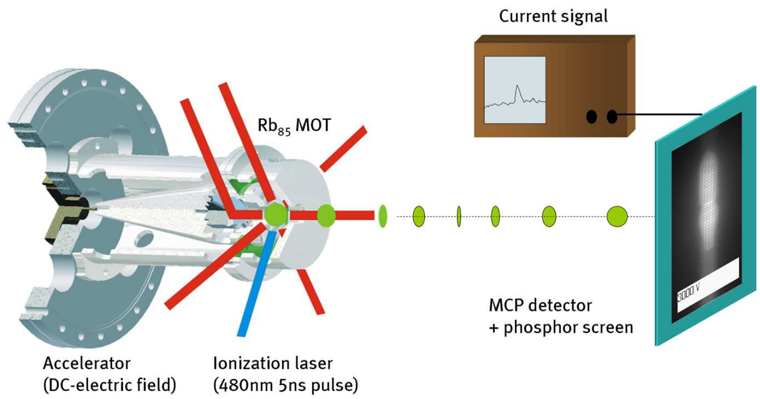

Figure 1: *A schematic overview of the experimental setup. Laser cooled and trapped Rubidium atoms are pulsed ionized and accelerated towards a detector.*

[1] S.B. van der Geer, M.P. Reijnders, M.J. de Loos, E.J.D. Vredenbregt, P.H.A. Mutsaers and O.J. Luiten, "Simulated performance of an ultracold ion source", J. Appl. Phys. 102, 094312 (2007)

Precise measurement of intensity correlation function for resonance fluorescence from an optical molasses

K. Nakayama[1], Y. Yoshikawa[1,2], H. Matsumoto[1,2], Y. Torii[1,2], T. Kuga[1,2]

[1]*PRESTO, CREST, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama, Japan*
[2]*Institute of Physics, University of Tokyo, 3-8-1, Meguro-ku, Komaba, Tokyo 153-8902, Japan.*

Intensity correlation measurement has been a standard diagnosis for the quantum statistical nature of physical particles. For photons from chaotic light sources, the zero delayed intensity correlation $g^{(2)}(0)$ is predicted to be 2, which insists bunching nature of successively emitted photons. A number of experiments with fluorescence from optical molasseses have shown this bunching effect clearly, although imperfect spatial coherence and time resolution have limited detailed examinations of $g^{(2)}(\tau)$. Here, in this poster, we report precise measurement of $g^{(2)}(\tau)$ for a light scattered from a continuously loaded optical molasses with a newly developed image-to-fiber scheme. The observed $g^{(2)}(\tau)$ showed not only the strong bunching but also an interference between the resonance fluorescence triplet.
Figure 1 (a) shows the experimental setup. The fluorescence to be measured was obtained from a continuously loaded optical molasses in an ultrahigh vacuum ($\sim 10^{-11}$ Torr) environment. A 2 cm-sized molasses was imaged onto the outside of the vacuum chamber, and a part of fluorescence was led into a single mode optical fiber. Splitting the light with a 50/50 fiber beam splitter, $g^{(2)}(\tau)$ for the two output modes was measured with two single photon counting modules (SPCMs), a time-to-amplitude converter (TAC) and a multi-channel analyzer (MCA). Figure 1 (b) shows a measured $g^{(2)}(\tau)$ for -22 MHz-detuned cooling beams. The decay time of the overall bunching was about 2 μs, which was determined by the Doppler width of the atoms. In addition, as shown in the inset, we observed a damped oscillation of $g^{(2)}(\tau)$ with a very short time scale. This can be interpreted as the interference between the frequency components of the resonance fluorescence triplet.

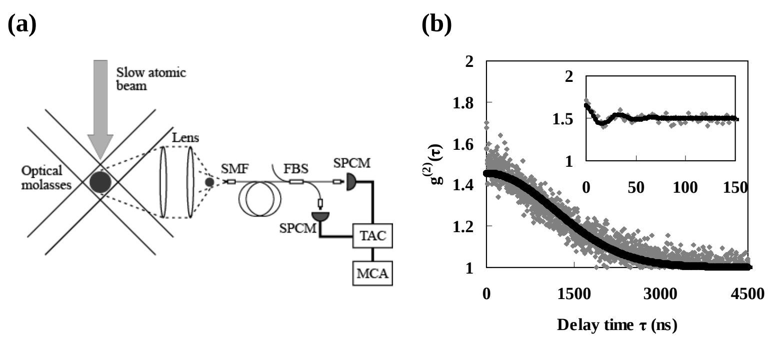

Figure 1: *(a) Experimental setup. (b) Intensity correlation function with -22 MHz-detuned cooling beams.*

Towards a Li-Rb Ring Interferometer

A. Öttl[1], R. Olf[1], E. Marti[1], E. Vogt[2], D. M. Stamper-Kurn[1]

[1]*Department of Physics, University of California, Berkeley, CA 94720, USA*
[2]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität, Heidelberg, Germany*

We report on the design and current status of our experimental approach to create non-trivial, multiply connected trap geometries for quantum gases and atom interferometry.
The novel setup is based on recent developments within the group [1] on magnetic ring traps. However, here we will employ specialized, micro-fabricated magnetic coils which generate very precise, smooth and tightly confining trapping fields. The diameter of the magnetic ring trap can be controlled and adjusted over a wide range from tens of microns to several millimeters. When employing the ring trap as a Sagnac-type atom interferometer with a pulsed source of thermal atoms, a large encircled area is advantages to increase the resolution of the gyroscope. However, working with smaller ring radii our goal is to fill the whole ring with degenerate quantum gases and to study the effects of a non-trivial topology on coherence and dynamics of Bose-Einstein condensates.
We will load the ring trap with both rubidium and lithium atoms, which allows us to explore diverse regimes of matterwave interferometry with bosonic and fermionic atoms of differing interaction strengths. Moreover, by making use of recently discovered betatron resonance[2] in ultracold atomic storage rings, not only the interferometers sensitivity could be stepped up, but it could also be turned into a short-range gravity detector.

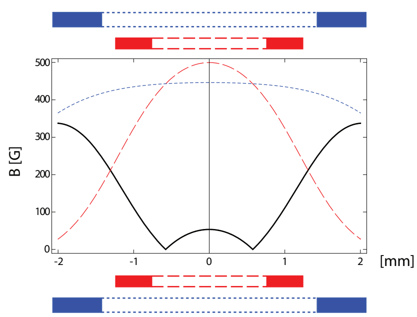

Figure 1: *The magnetic ring trap is generated by the field of a pair of curvature coils (dashed), subtracting a homogenous bias by a pair of antibias coils (dotted). The annulus shaped magnetic zero is transformed in a time-orbiting manner in a biased harmonic potential. The diameter of the ring trap can be varied from tens of microns to several millimeters, radial trap frequencies on the order of a kHz are anticipated. On the right hand side is an artists impression of a quantum fluid in a ring trap.*

[1]S. Gupta, K. W. Murch, K. L. Moore, T. P. Purdy, and D. M. Stamper-Kurn, Phys. Rev. Lett. **95**, 143201
[2]K. W. Murch, K. L. Moore, S. Gupta, and D. M. Stamper-Kurn, Phys. Rev. Lett. **96**, 013202

Adjustable microchip ringtraps for cold atoms and molecules.

Paul Baker[1], Matthew B. Squires[1], James A. Stickney[2], James Scoville[1], Steven M. Miller[1]

[1]*Air Force Research Laboratory, Hanscom AFB, MA 01731*
[2]*Space Dynamics Laboratory, Bedford, MA 01730*

We describe the design and function of a circular magnetic waveguide for deBroglie waves on a microchip. The guide is a two-dimensional magnetic minimum for trapping weak-field seeking states of atoms or molecules with a magnetic dipole moment. The waveguide is created entirely by current carrying wires lithographically patterned on a single layer chip with or without vias. The design consists of overlapping three and four wire waveguides in a circle; about a common radius. We describe the geometry and time-dependent currents of the wires and show that it is possible to form a circular waveguide while minimizing perturbation resulting from leads or wire crossings. This maximal area geometry is suited for rotation sensing with atom interferometry via the Sagnac effect using either cold thermal atoms and molecules or Bose-condensed systems.

Output coupling solution for magnetically trapped spinor condensates

R. Vasile[1], B. T. Torosov[1,2], K.-A. Suominen[1]

[1]*Department of Physics, University of Turku, FI-20014 Turun yliopisto, Finland*
[2]*Department of Physics, University of Sofia, Bulgaria*

In the last two decades many different ways of trapping matter in certain region of space have been developed. One of the most fascinating topic is that of the magnetic traps for neutral atoms. In this case a spatially variable magnetic field can trap atoms possessing a hyperfine structure characterized by a quantum number F. Once these atoms are trapped, by coupling the different levels with an rf-field is possible to cool them in order for the atoms to reach temperatures in which Bose-Einstein condensation is established efficiently (evaporative cooling). Once the BEC is prepared is also possible to coherently control the release of the condensate from the trap using again pulsed rf-fields (output coupling) [1].

Both evaporative cooling and output coupling require solutions for the dynamics of the multistate condensate in the presence of the time-dependent rf-field. Even if there exist many numerical algorithms able to solve the problem, a general analytic exact result is still unknown. We show here a method for solving the dynamics of the coupled system for any value of the quantum hypefine number F and starting from any superposition of states. Previously such solutions have usually assumed that initially only one of the extreme angular momentum states $M_F = \pm F$ has been populated[2]. Our method is based on a particular decomposition of higher spin states in terms of a certain number of spin 1/2 systems states (Majorana decomposition)[3]. This means that if we know the solutions for the $F = 1/2$ system we can use these to construct the solutions for any higher value of F.

In this work we present the solution of the dynamics in the case of two different time-dependent models. The first one is the interaction with a chirped pulse described by the well-known Landau-Zener model. In the second one we consider an oscillating field (Rabi model). The interaction of the initially trapped spinor condensate with these pulses allows one to construct many interesting superposition of states which, in principle, could be verified in experiments looking at the final populations of the released condensate[1,4].

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Trapping hydrogen atoms in a neon-gas matrix: A theoretical simulation

S. Bovino[1], P. Zhang[1], V. Kharchenko[1,2], A. Dalgarno[1]

[1] *ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA*
[2] *Department of Physics, University of Connecticut, Storrs, CT, USA*

Hydrogen is of critical importance in atomic and molecular physics and the development of a simple and efficient technique for trapping cold and ultracold hydrogen atoms would be a significant advance. In this study we simulate a recently proposed[1] trap-loading mechanism for trapping hydrogen atoms in a neon matrix.
Accurate ab initio quantum calculations are reported of the neon-hydrogen interaction potential and the orientation-dependent elastic scattering cross sections that control the thermalization of initially energetic atoms are obtained. They are then used in solving the linear Boltzmann equation. Based on the simulations we discuss the prospects of the technique.

[1] R. Lambo, C. C. Rodegheri, D. M. Silveira and C. L. Cesar, Phys. Rev. A **76**, 061401, 2007.

Near-field Diffraction Optical Microtraps for Atoms

T. N. Bandi[1], V. G. Minogin[1,2], S. Nic Chormaic[1,3]

[1] *Tyndall National Institute, Cork, Ireland*
[2] *Institute of Spectroscopy, Russ. Ac. of Sciences, 142190 Troitsk, Moscow Region, Russia*
[3] *Physics Department, University College Cork, Cork, Ireland*

The development of new techniques to trap and manipulate neutral atoms is of great interest due to the impact such advances could have on the evolution of atom-based quantum information technologies. In this paper, we propose and present a quantitative analysis of atom microtraps based on near-field Fresnel diffraction off a thin circular aperture. The aperture size is approximately equal to or greater than the incident optical wavelength and the diffraction is characterized by a Fresnel number, $N_F \geq 1$.

Similar to other approaches employing laser fields[1], the operation of the proposed near-field microtraps relies on dipole potentials and their corresponding dipole gradient forces. However, whereas in other approaches the gradient force arises from the non-uniform field distribution over the laser beam cross-section or over the wavelength of the laser light, here the gradient force stems from the optical field non-uniformity over the aperture diameter. Consequently, atom microtraps can store atomic microclouds with characteristic dimensions equivalent to or less than the field wavelength. Such microclouds could be used for site-selective manipulation of atoms. We analyze the field distribution in the vicinity of a small, circular aperture in a thin screen, and calculate the dipole potential of the atom in the diffracted near-field. Our analysis of the Fresnel microtraps shows that, at a moderate intensity of the light field of about 10 W/cm^2, the traps are able to store atoms with a kinetic energy of about 100 μK during time intervals of around one second.

The proposed technique could be extended in order to fabricate an array of atom microtraps (see Fig. 1) and, accordingly, produce a large number of trapped atomic microensembles from a single initial atomic cloud or beam.

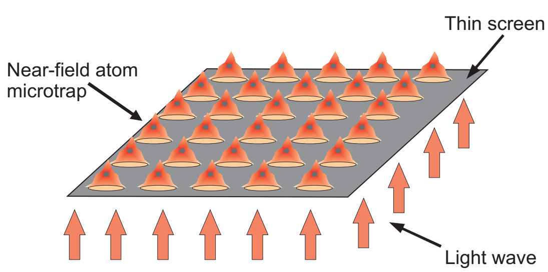


Figure 1: *Schematic of an atom microtrap array.*

[1] G. Birkl, F. B. J. Buchkremer, R. Dumke, and W. Ertmer, Opt. Commun. 191, 67 (2001).

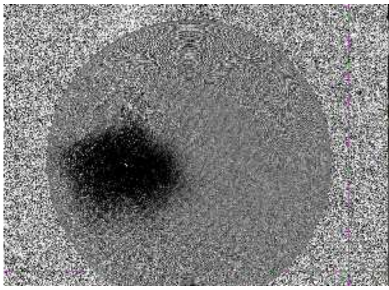
Ultra cold atoms in Parametrically driven magnetic potentials

Dahyun Yum, Jina Park, Wonho Jhe

Department of Physics, Seoul National University, Seoul, Korea

A system of magneto optically trapped atoms in a parametrically driven potential makes two attractors and have oscillatory motions[1] and Spontaneous Symmetry Breaking, ising like phase transition, dynamic phase transition and more subjects were studied . For bose-einstein condensates in modulating potentials, many interesting results are reported.(ex; collective excitations[2], Faraday waves[3]) We also have interests in special phenomena of magnetically trapped ultra cold atoms at oscillating potential and expect that it provide some clues of the studies of atom-atom interactions(especially attractive interaction).

In our experiments, Rb^{87} atoms are gathered at the 1st chamber(or gathering chamber) and transferred to the 2nd glass chamber(or experimental chamber) by laser. The cooled atoms are recaptured and loading at a magnetic potential(TOP-trap) after compressing, molasses cooling and optical pumping. We have a schedule to cool down the rubidium atoms by evaporative cooling and modulate the magnetic bias fields. As the results, Oscillating motions are expected and from that phenomena, some information of relations between atom and atom would be obtained.



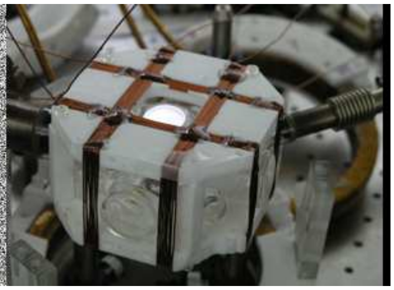


Figure 1: *Absorption image of Trapped Rb^{87} atoms(left).*

Figure 2: *Experimental setup photos of 2nd glass chamber with TOP coil(right).*

[1] Kihwan kim et. al., Phys. Rev. Lett. **96**, 150601(2006)
[2] D. S. Jin et. al., Phys. Rev. Lett. **77** 420(1996)
[3] P. Engels et. al., Phys. Rev. Lett. **98** 095301(2007)

Novel Coherent Optical Medium Based on Buffer-Gas-Cooled Rb Vapor

Tao Hong[1,2], A. V. Gorshkov[1], D. Patterson[1], A. S. Zibrov[1], J. M. Doyle[1], M. D. Lukin[1], M. G. Prentiss[1]

[1] *Harvard-MIT Center for Ultracold Atoms and Department of Physics, Harvard University, Cambridge, MA 02138*
[2] *Joint Quantum Institute, Department of Physics, University of Maryland, College Park, MD 20742*

We demonstrate a novel coherent optical medium with high optical depth and low Doppler broadening that offers metastable states with low collisional and motional decoherence. In our approach, helium buffer gas cools ^{87}Rb atoms to below 7 K, while at the same time slowing atom diffusion. We demonstrate that electromagnetically induced transparency (EIT) allows 50% transmission in a medium with initial OD $>$ 70. Slow pulse propagation experiments in this medium yield a large delay-bandwidth product. Efficient four-wave mixing is observed in the high-OD regime, resulting ina pronounced modification of the atomic optical response. [1]

[1] For more details, please look at http://arXiv.org/abs/0805.1416.

Trapping Atoms in the Vicinity of a Persistent Supercurrent Atom Chip

T. Mukai[1,2], C. Hufnagel[1,2], F. Shimizu[1,2,3]

[1] *NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan*
[2] *CREST, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan*
[3] *Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 113-8585, Japan*

We have succeeded in producing a persistent supercurrent atom chip that can trap atoms in the vicinity of a solid surface with a practically noise free magnetic field. As plotted in Fig.1, about one million rubidium atoms are trapped below the atom chip which has persistent current driving through a MgB_2 superconducting closed loop circuit on a sapphire substrate. Apart from trapping atoms with a persistent supercurrent, we have also succeeded in controlling the persistent current with an on chip thermal switch driven by a laser[1].
The trapping lifetime of the persistent supercurrent atom chip was measured to be about 10 s at 30 μm away from the chip surface. It is significantly longer than that of a normal conducting atom chip.

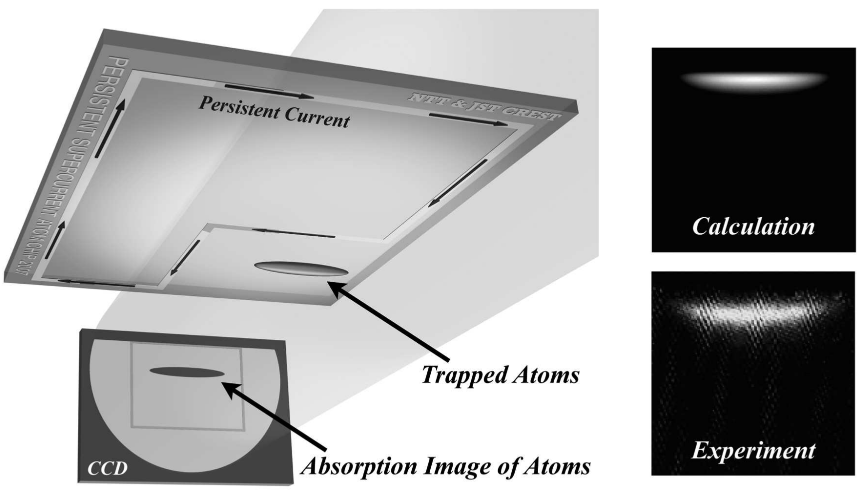


Figure 1: *(left) Image of the experiment. (right) Absorption image of the trapped atoms and the calculated potential shape.*

[1] T. Mukai, C. Hufnagel, et al., “Persistent Supercurrent Atom Chip”, Phys. Rev. Lett. 98, 260407 (2007)

Absolute frequency stabilisation of a laser to ions in a discharge

T. J. Weinhold, E. W. Streed, D. Kielpinski

Centre for Quantum Dynamics, Griffith University, Brisbane, Qld, 4111, Australia

Experiments in atomic physics commonly require lasers with long term frequency stability to operate within a few MHz of an atomic transition. While for wavelength in the near IR and visible lasers can be locked to a multitude of suitable references, that can be derived from atomic vapour cells with well refined spectroscopic techniques, such references are rather sparse in the blue and UV.

Here we present the locking of a tuneable UV laser diode to the optical absorption signal from Yb^+ ions produced in a hollow cathode discharge lamp. Using a form of Zeeman polarisation spectroscopy we derive a frequency locking signal used to provide long term frequency stabilisation of the laser system. We measure the absolute frequency stability by detecting the fluorescence signal of a laser-cooled crystal of $174\mathrm{Yb}^+$ ions in a linear Paul trap. Such crystals typically exhibit a lifetime-limited linewidth ($20MHz$) of the dipole-allowed optical resonance, thus providing an accurate and sensitive frequency reference for our laser lock. We find fractional frequency instabilities lower than 3×10^{-10} at 20s and find absolute frequency fluctuations of less than $1.5M$Hz RMS in 1000s. Expanding our technique to other ion species will greatly extend the range of frequency references in the blue and UV and thus allow the implementation of such lasers in atomic physics experiments.

Double U-type Magneto-optical Trap on an Atom Chip

H. Yan[1,2,3], G. Q. Yang[1,2,3], T. Shi[1,2,3], J. Wang[1,2], M. S. Zhan[1,2]

[1]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*
[2]*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*
[3]*Graduate School of the Chinese Academy of Sciences, Beijing 100080, China*

Atom chip is one of the best candidates for integrating and miniaturizing the Magneto-optical Trap (MOT) for neutral atoms [1]. A lot of novel applications have been proposed and realized on the atom chip [1,2]. Researchers have proposed some schemes to realize a double MOT on an atom chip [3,4]. We demonstrated experimentally the double U-type Magneto-optical trap based on an atom chip. The double quadrupole magnetic fields are produced by two separate U-shaped micro-lines on an atom chip as shown in Figure 1; double MOTs are realized simultaneously in two separate double quadrupole magnetic fields as shown in Figure 2. More than 10^6 atoms are trapped in both U-traps. This will provide an excellent physical base for much further researches.

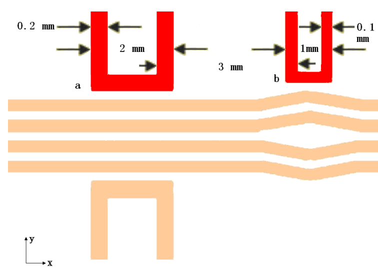


Figure 1: *Diagram of our atom chip, a, b are two U-shape wires.*

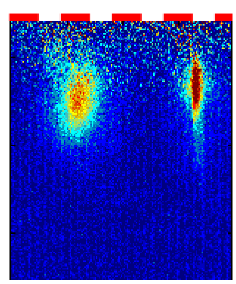


Figure 2: *Fluorescence picture of the double U-type MOT.*

[1]J. Fortagh and C. Zimmermann, "Magnetic Microtraps for Ultracold Atoms", Rev. Mod. Phys. **79** 235(2007)

[2]R. Folman, P. Krger, J. Schmiedmayer, J. Denschlag, and C. Henkel, "Microscopic Atom Optics: From Wires to an Atom Chip", Adv. At. Mol. Opt. Phys. **48**, 263(2002)

[3]M. Yun and J. Yin, "Controllable Double-well Magneto-optic Atom Trap with a Circular Current-carrying Wire", Opt. Lett. **30**, 696(2005)

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Laser Cooling and Trapping of Barium

S. De, U. Dammalapati, K. Jungmann, L. Willmann

KVI, University of Groningen, Groningen, The Netherlands

We demonstrated efficient laser cooling and trapping of the heavy alkaline earth element barium (Ba) on the strong $^1S_0$-$^1P_1$ transition. Losses from the cooling cycle due to the branching into metastable D-states of 1:330(30) have to be compensated by several repumplasers. Seven laser were employed at the same time to collect Ba atoms into a magneto optical trap. A capture efficiency from an effusive atomic beam of order of 1% was achieved. It was limited by the available laser power at the repumping transitions wavelengths. This work is the preparation of experiments with rare isotopes of radium (Ra), which is the chemical homologue Ba. Ra isotopes have attracted attention due to high their high sensitivity to symmetry violating effects. In particular, they offer the highest known enhancement factors for possible permanent electric dipole moments (EDM's), both of electrons and of nuclei in several isotopes which have nuclear spin. These arise from close lying states of opposite parity in the atomic shell (^{3}P and ^{3}D) [1] or in the nucleus where they are associated with interference of quadrupole and octopole deformations in some nuclei near the region of the valley of stability [2] Furthermore, isotope shifts of the $^3D_{1,2}$-$^1P_1$ transitions have been determined. They reveal large large shifts for odd isotopes with nuclear spin of I=3/2 compared to the even isotopes [3]. This could indicate a reason for the sensitivity of the metastable ^{3}D-states to nuclear EDM's in the $^3D_2$-state for Ra.

[1] V. V. Flambaum, Phys. Rev. A 60, R2611 (1999); V.A. Dzuba et al., Phys. Rev. **A61**, 062509 (2000).

[2] J. Dobaczewski et al., Phys. Rev. Lett. **94**, 232502 (2005); V.V. Flambaum et al., Phys. Rev. **C 68**, 035502 (2003).

[3] U. Dammalapati et al., arXiv:0805.2022 (2008).

AC electric trapping of Rb atoms

S. Schlunk[1,2], A. Marian[1], A. K. Duraisamy[1], W. Schöllkopf[1], G. Meijer[1]

[1] *Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany*
[2] *FOM-Institute for Plasmaphysics Rijnhuizen, Nieuwegein, The Netherlands*

We demonstrate trapping of an ultracold gas of Rb atoms in a macroscopic AC electric trap[1]. In analogy to a Paul trap, three dimensional confinement is obtained by switching between two saddle-point configurations of the electric field. This is realized by applying two sets of high voltages to the ring and end-cap electrodes of the cylindrically symmetric trap. In one configuration (left part of Fig. 1) the electric field strength is characterized by a maximum along the radial direction and a minimum along the z-axis. Due to the second-order Stark effect all sub-levels of ground-state Rb are high-field seeking and experience attractive forces along the radial direction and repulsive forces along the z-axis. In the other configuration (right part of Fig. 1) the role of the forces is reversed. By switching between both configurations with a frequency around 60 Hz we achieve stable trapping of about 3×10^5 Rb atoms in the 1 mm^3 large and several microkelvin deep trap with a lifetime on the order of 10 s. Absorption imaging at different phases of the AC switching cycle allows to directly visualize the dynamic confinement of the atoms. In addition, the gradual formation of a stably trapped cloud is observed and the trap performance is studied as a function of switching frequency and symmetry of the switching cycle. Furthermore, the electric field in the trap is mapped out by imaging the atom cloud while the fields are still on[2].

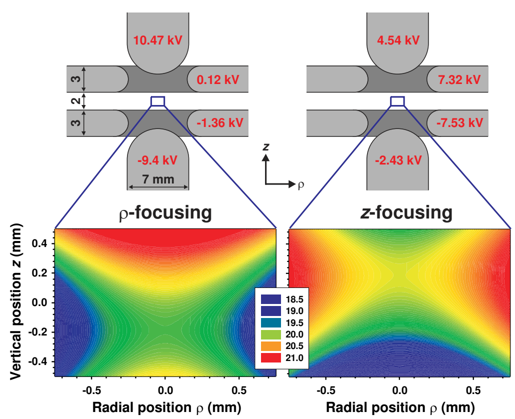

Figure 1: *The cylindrically symmetric AC electric trap consists of two ring and two end-cap electrodes. Dynamic confinement is achieved by switching between two sets of high voltages applied to the electrodes. The color scale marks the field strength in kV/cm.*

[1] S. Schlunk, A. Marian, P. Geng, A.P. Mosk, G. Meijer, and W. Schöllkopf, "Trapping of Rb Atoms by ac Electric Fields", Phys. Rev. Lett. 98, 223002 (2007).

[2] S. Schlunk, A. Marian, W. Schöllkopf, and G. Meijer, "ac electric trapping of neutral atoms", Phys. Rev. A 77, 043408 (2008).

A Cigar-Shaped Cold Atom Cloud in the MOT with Large Optical Density

Yen-Wei Lin[a], Hung-Chih Chou[a], Prashant P. Dwivedi[b], Ying-Cheng Chen[b], Ite A. Yu[a,1]

[a] *Department of Physics, National Tsing Hua University, Hsinchu 300, Taiwan*
[b] *Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 106, Taiwan*

We demonstrate a simple method to increase the optical density (OD) of cold atom clouds produced by a magneto-optical trap (MOT).[2] A pair of rectangular anti-Helmholtz coils is used in the MOT to generate the magnetic field that produces the cigar-shaped atom cloud. With 7.2×10^8 ^{87}Rb atoms in the cigar-type MOT, we achieve an OD of 32 as determined by the slow light measurement and this OD is large enough such that the atom cloud can almost contain the entire Gaussian light pulse (see Fig.1). Compared to the conventional MOT under the same trapping conditions, the OD is increased by about 2.7 folds by this simple method. In another MOT setup of the cigar-shaped Cs atom cloud, we achieve an OD of 105 as determined by the absorption spectrum of the $|6S_{1/2}, F = 4\rangle \rightarrow |6P_{3/2}, F' = 5\rangle$ transition (see Fig. 2).

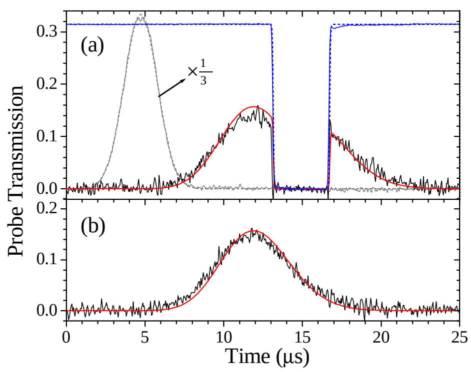

FIG. 1

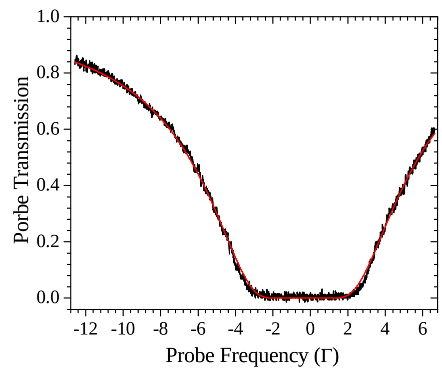

FIG. 2

Figure 1: *The storage and retrieval of the probe pulse in (a) and the slow probe pulse under the constant presence of the coupling field in (b). Solid gray, black, and blue lines are the experimental data of the input and output probe pulses and the coupling field. The input probe pulse is plotted with the size reduced to one third. Dashed gray and blue lines in (a) are the functions of the input probe pulse and the coupling field used in the calculation. Solid red lines in (a) and (b) are the best fits calculated at* $(OD, \Omega_c, \gamma) = (32, 0.330\Gamma, 7.1 \times 10^{-4}\Gamma)$.

Figure 2: *Transmission spectrum in laser-cooled cigar-shaped Cs atom cloud. Black and red lines are the experimental data and the best fit. The fitting function is* $y = \exp\{-OD/[1 + 4(x - x_0)^2]\}$, *and* $OD = 105$ *and* $x_0 = -0.35\Gamma$ *for the best fit.*

[1] E-mail address: yu@phys.nthu.edu.tw
[2] Y. W. Lin, H. C. Chou, P. P. Dwivedi, Y. C. Chen, and I. A. Yu, Opt. Express **16**, 3753 (2008).

Collective Excitations of Trapped Imbalanced Fermion Gases

A. Lazarides, B. Van Schaeybroeck

Instituut voor Theoretische Fysica, Katholieke Universiteit Leuven,
Celestijnenlaan 200 D, B-3001 Leuven, Belgium.

We present a theoretical study of the collective excitations of a trapped imbalanced fermion gas at unitarity, when the system consists of a superfluid core and a normal outer shell. We formulate the relevant boundary conditions and treat the normal shell both hydrodynamically and collisionlessly. For an isotropic trap, we calculate the mode frequencies as a function of trap polarization. Out-of-phase modes with frequencies below the trapping frequency are obtained for the case of a hydrodynamic normal shell. For the collisionless case, we calculate the monopole mode frequencies, and find that all but the lowest mode may be damped.

Trapped Phase-Segregated Bose-Fermi Mixtures and their Collective Excitations

B. Van Schaeybroeck, A. Lazarides

Instituut voor Theoretische Fysica, Katholieke Universiteit Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium

In recent experiments, the creation of phase-segregated Bose-Fermi systems was reported[1]. We present a theoretical study of their collective excitations at zero temperature. First we analytically solve the Boltzmann-Vlasov equation for the fully-polarized fermionic phase to extract the monopole mode frequencies and their damping rates as a function of the fraction of fermions in the trap. A criterion for damping to occur, also valid for multipole excitations, is established. We then use a hydrodynamic approximation for the fermions to obtain further results concerning in-phase and out-of-phase motions of the bosonic core and the surrounding fermionic shell[2].

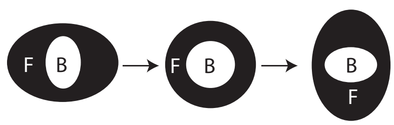

Figure 1: *Out-of-phase collective excitations of trapped phase-segregated Bose-Fermi gases. The trap consists of a bosonic (B) core and a surrounding fermionic (F) shell which move out-of-phase.*

[1] S. Ospelkaus, C. Ospelkaus, L. Humbert, K. Sengstock and K. Bongs, Phys. Rev. Lett **97**, 120403 (2006); M. Zaccanti, C. D'Errico, F. Ferlaino, G. Roati, M. Inguscio and G. Modugno, Phys. Rev. A **74**, 041605(R) (2006).

[2] A. Lazarides and B. Van Schaeybroeck, Phys. Rev. A **77**, 041602(R) (2008).

BEC as a Tool for Quantum Measurement

S. G. Bhongale, H. Pu

Physics and Astronomy MS-61, Rice University, 6100 Main Street, Houston, TX 77005, USA

Recently a new avenue in cold atom physics has opened up where by the prospects of- Bose-Einstein Condensates formed in trapped atom experiments as a tool rather than a “system-to-study” has been investigated. One such tool that has been recently proposed is a “Quantum Level” that is a quantum analog of the commonly used “Spirit Level”.
In the present work we propose a robust probe for detecting Bardeen-Cooper-Schrieffer (BCS) superfluidity in a trapped two-component Fermi gas.In hear the probe corresponds to a Bose condensed state (BEC) of some third species of atoms- ‘probe-atoms’ confined to a narrow trap. This detection scheme is based on the extreme control of atom-atom interactions that is made available by techniques based on scattering resonances such as a magnetic/optical Feshbach. We show that when the experimental parameters are fine tuned within a certain region of parameter space, the density of the bosonic atoms give a direct measure of the BCS gap associated with the fermions.

Bragg Spectroscopy of a Strongly Interacting Fermi Gas

G. Veeravalli, E. D. Kuhnle, P. Dyke, W. Rowlands, P. Hannaford, C. J. Vale

ARC Centre of Excellence for Quantum Atom Optics, Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne, 3122, Australia

Bragg spectroscopy offers a high resolution means to probe the constituents of ultracold atomic gases[1]. Bragg scattering is achieved using two far detuned laser beams with a small tunable frequency difference δ to create a moving periodic potential. The Bragg resonance condition is $\delta = 2\hbar k_L^2/m$ where k_L is the wavevector of the laser and m is the mass of the particles being scattered. In a strongly interacting Fermi gas, these particles can be free atoms (with mass m), tightly bound molecules (mass $2m$) or correlated pairs, depending on the sign and strength of the interactions.
We have performed Bragg spectroscopy of a highly degenerate gas of fermionic ^{6}Li in a 50/50 mixture of states $|F = 1/2, m_F = +1/2\rangle$ and $|1/2, -1/2\rangle$ across the broad Feshbach resonance at 834 G. Free particle Bragg scattering is achieved by turning off the optical dipole trap and applying a Bragg pulse after 4 ms expansion. Figures 1(a) and (b) show scattering of molecules and atoms, below and above the Feshbach resonance, respectively. Scattered atoms travel twice as far as molecules in the same time of flight. Spectra obtained using trapped gases relate to the dynamic structure factor for $2k_L \approx 5k_F$ in our experiments[2]. These are dominated by features corresponding to the presence of molecules on the BEC side of the resonance, pairs and free atoms at unitarity and free atoms far on the BCS side, Fig. 1(c). Near unitarity, the fraction of pairs scattered depends strongly on the density (pre-expansion time) of the gas demonstrating how the existence of pairs relies on the presence of the strongly interacting cloud.

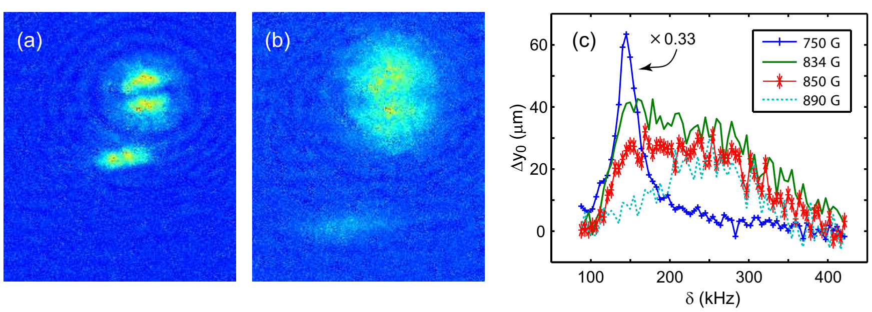

Figure 1: *Bragg scattering of (a) molecules from a molecular BEC and (b) atoms from a highly degenerate Fermi gas, at 730 G and 870 G, respectively. The field of view for both images is 650 μm by 880 μm. (c) Bragg spectra of trapped gases at various magnetic fields across the 834 G Feshbach resonance.*

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Bose-Fermi Mixtures on an Atom Chip

D. A. Smith, M. Kuhnert, M. Gring, Ch. v. Hagen, J. Schmiedmayer

ATI TU-Wien, Vienna, Austria

We are in the process of building a new experiment to investigate Bose-Fermi mixtures in the 3D, effectively 1D, and 3D/1D cross-over regimes. Our smooth atom chip potentials should allow the creation of very elongated traps (axial confinement less than 1 Hz, radial confinement greater than 5 kHz) that will enable us to investigate the Rb-K Bose-Fermi mixture in a single low-dimensional system. The current status of the experiment will be reported.

Finite temperature dynamics of a strongly interacting ultracold Fermi gas.

S. Riedl[1,2], E. R. Sánchez Guajardo[1], K. Kohstall[1], J. Hecker Denschlag[1], R. Grimm[1,2]

[1] *Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria*
[2] *Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*

We present experimental results on the dynamics of a strongly interacting ultracold Fermi gas. By use of a Feshbach resonance we are able to tune the scattering length between fermions. Far from resonance there is a BEC of diatomic molecules in one limiting case, and a BCS state in the other. In the BEC-BCS crossover we realize a strongly correlated system. We probe the dynamics and dissipation in this regime by exciting different collective modes and by rotating the cloud[1,2,3]. In particular, we study different finite temperatures[3]. The resulting phase diagram for the scissors mode shows a region of nonsuperfluid hydrodynamics (see Fig. 1). In addition, the results show unexpected features close to the Feshbach resonance, *i.e.*, a downshift of the radial surface mode frequency and a second peak in the damping of the scissors mode at low finite T (see Fig. 1), that await a theoretical description. The comparison of our finite temperature data with recent theoretical results[4] provides new insight into the role of pairing. Last, we explore a new experimental route towards measuring T_c by rotating the cloud and show preliminary results.

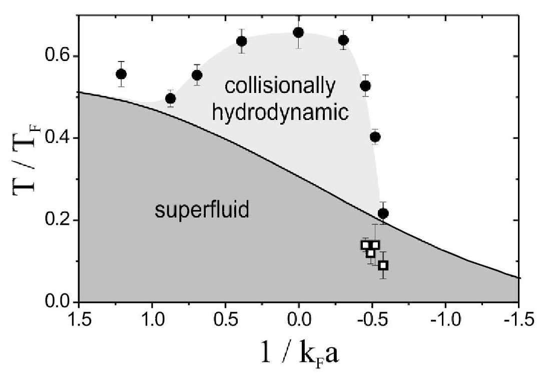

Figure 1: *Phase diagram for the scissors mode showing a nonsuperfluid hydrodynamic region (filled circles). The open squares correspond to an unexpected feature in the damping. The solid line shows a theoretical curve for the phase transition to superfluidity*[5].

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Using photoemission spectroscopy to probe a strongly interacting Fermi gas

J. P. Gaebler, J. T. Stewart, D. S. Jin

JILA, Quantum Physics Division, National Institute of Standards and Technologies and Deptartment of Physics, University of Colorado, Boulder, CO 80309-0440 USA

Ultracold atom gases provide model systems in which many-body quantum physics phenomena can be studied. Recent experiments on Fermi gases have realized a phase transition to a Fermi superfluid state with strong interparticle interactions. This system is a realization of the BCS-BEC crossover connecting the physics of BCS superconductivity and that of Bose-Einstein condensation (BEC). While many aspects of this system have been investigated, it has not yet been possible to measure the single-particle excitation spectrum, which is a fundamental property directly predicted by many-body theories. Here we show that the single-particle spectral function of the strongly interacting Fermi gas at $T \approx T_c$ is dramatically altered in a way that is consistent with a large pairing gap. We use photoemission spectroscopy to directly probe the elementary excitations and energy dispersion in the Fermi gas of atoms. In these photoemission experiments, an rf photon ejects an atom from our strongly interacting system via a spin-flip transition to a weakly interacting state. We measure the occupied single-particle density of states for an ultracold Fermi gas of ^{40}K atoms at the cusp of the BCS-BEC crossover and on the BEC side of the crossover, and compare these results to that for a nearly ideal Fermi gas. Our results probe the many-body physics in a way that could be compared to data for high-Tc superconductors. This new measurement technique for ultracold atom gases, like photoemission spectroscopy for electronic materials, directly probes low energy excitations and thus can reveal excitation gaps and/or pseudogaps. Furthermore, this technique can provide an analog to angle-resolved photoemission spectroscopy (ARPES) for probing anisotropic systems, such as atoms in optical lattice potentials.

Superfluid phase transition in the unitarity limit

M. Horikoshi[1], S. Nakajima[2], Y. Inada[1,3], M. Ueda[1,2], T. Mukaiyama[1]

[1]*ERATO Macroscopic Quantum Control Project, JST, Yayoi, Bunkyo-ku, Tokyo, Japan*
[2]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*
[3]*Department of applied Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*

A magnetically tunable interaction via Feshbach resonance enables ultracold fermionic atoms to achieve the unitarity limit where an s-wave scattering length diverges and universal thermodynamics is expected to emerge. In the unitarity limit, the thermodynamics can be described only by the temperature and the atomic density, and the superfluid temperature (Tc) divided by the Fermi temperature is among such universal parameters. However, the technique to determine the temperature has not been well established due to strong interactions and the nature of a "fermion pair" condensate; thus understanding of the thermodynamics of the system is far from complete. Therefore reliable Tc determination remains to be among the most important challenges of the unitary gas.
In this research, we have investigated thermodynamics of unitary gas with various evaluation methods. We prepare 10^6 of ultracold balanced 2-spin ^{6}Li atoms in the lowest spin states in an optical dipole trap with the magnetic field set at 834G of the Feshbach resonance. Temperature of the unitary gas is controlled by the optical trap depth.
We have observed emergence of molecular condensates after rapid field ramping to BEC side, namely projection. It is believed that with the method of projection a fermion pair is converted into a molecule while the center-of-mass (COM) momentum of the pair is conserved during the projection. Therefore, emergence of molecular condensates corresponds to emergence of fermion-pair condensates. Temperature at the Tc point is evaluated by Bragg spectroscopy of molecules after projection, which is the technique of temperature measurement developed for strongly-interacting molecules in the BEC side [1]. This method can be used in the unitarity limit and also in the BCS side in principle with the proviso that the COM momentum distribution of pairs faithfully reflect the temperature of the system. To establish a model-independent thermometry of the system, the relation between temperatures before and after the projection needs to be fully understood.
In order to vindicate the validity of our method, we have determined the Tc point from the heat capacity measurement according to the method of the Duke group[2]. We believe that this comparison helps understand the mechanism of projection and improves the thermometry in the BCS-BEC crossover.

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p-wave Feshbach Molecules of ^{6}Li$_{2}$

Y. Inada[1,2], M. Horikoshi[1], S. Nakajima[1,3] M. Kuwata-Gonokami[1,2], M. Ueda[1,3], T. Mukaiyama[1]

[1]*ERATO Macroscopic Quantum Control Project, JST, Yayoi, Bunkyo-ku, Tokyo, Japan*
[2]*Department of Applied Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*
[3]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*

Fermionic p-wave superfluidity present a rich variety of novel phenomena caused by the complex order parameters. Recent experimental advances in controlling interactions of ultracold atomic gases have awakened expectations for realizing p-wave superfluidity of fermionic atoms, which would offer great opportunities to study superfluid phases with the precise control of atomic physics. To discuss the feasibility of p-wave superfluidity, one needs to know the thermalization time scale and the stability of the gas determined by the elastic and inelastic collisions.

We have observed the formation of p-wave Feshbach molecules for all three combinations of the two lowest atomic spin states of ^{6}Li. For a pure molecular sample in an optical trap, we have measured the elastic and inelastic collision rates of p-wave molecules[1]. By sweeping the magnetic field to a value near the p-wave Feshbach resonance, p-wave molecules were created from a degenerate Fermi gas of the atoms. After the formation of the molecules, the residual atoms were removed from the trap by applying the resonant light pulse in order to prepare a pure molecular sample. The dimer-dimer inelastic collision rate is determined from the measurement of the loss of molecules as a function of the hold time. The measured inelastic collision rate is almost independent of the magnetic field detuning on the bound side of the Feshbach resonance. The atom-dimer collision rate is extracted from the loss measurement of the atom-molecule mixture. In the process of creating molecules, breathing mode oscillations were spontaneously excited due to the mismatch of the initial real space distribution of molecules from the thermal equilibrium. The dimer-dimer elastic collision rate is estimated from the thermalization time of the oscillation. Our results show the ratio of elastic and inelastic rate is five. In the current experimental condition, the phase space density of the molecular gas is estimated to be 4×10^{-3}.

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The Interacting Fermi-Fermi Mixture of ^{6}Li and ^{40}K

A.-C. Voigt[1,2], M. Taglieber[1,2], L. Costa[1], T. Aoki[1,2], T. W. Hänsch[1,2], K. Dieckmann[1,2]

[1]*Ludwig-Maximilians-University of Munich, Schellingstr. 4, 80799 Munich, Germany*
[2]*Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*

We report on the generation of an interacting quantum degenerate Fermi-Fermi mixture of two different atomic species, ^{6}Li and ^{40}K. Due to the differing internal and external properties of the two components, this mixture is an excellent candidate to study quantum phases of fermionic mixtures in the strongly interacting regime. We first describe the combination of trapping and cooling methods that proved crucial to successfully cool the mixture[1]. The quantum degenerate mixture is realized employing sympathetic cooling of the fermionic gases by an evaporatively cooled bosonic ^{87}Rb gas. In particular, we study the last part of the cooling process and show that the efficiency of sympathetic cooling of the ^{6}Li gas by ^{87}Rb is significantly increased by the presence of ^{40}K through *catalytic* cooling. We then describe our recent results on the location of Feshbach resonances between ^{6}Li and ^{40}K and on the creation of heteronuclear ^{6}Li-^{40}K molecules.

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Realization of a Spin-1 Fermi Gas

J. H. Huckans, J. R. Williams, E. L. Hazlett, R. W. Stites, K. M. O'Hara

The Pennsylvania State University, University Park, PA 16802, USA

Fermi gases with three (rather than two) internal degrees of freedom are predicted to exhibit novel phenomena not observed in spin-1/2 Fermi systems. For example, multibody cluster states have been predicted to occur in the strong coupling regime [1, 2] and, in contrast to two-component Fermi superfluids, superfluidity is predicted to drive magnetism in a three-component mixture [3]. While it would be exciting to test these and other theoretical predictions in an ultracold gas of fermions, it is not obvious that such a mixture can be stabilized against two- and three-body inelastic processes.
A mixture of ^{6}Li fermions in the three lowest energy hyperfine states is a promising candidate for such studies since inelastic two-body collisions only arise due to weak dipole-dipole interactions and are expected to be suppressed at high magnetic fields. Furthermore, each of the three possible pairwise interactions can be tuned via s-wave Feshbach resonances predicted to occur at 690 Gauss, 811 Gauss and 834 Gauss [4]. For very large fields, the gas becomes electron spin polarized and the two-body scattering lengths all asymptote to the large and attractive triplet scattering length $a = -2160a_0$. Three-body recombination, however, is not expected to be suppressed as it is in a two-state mixture.
We have confined this three-state mixture of fermionic lithium atoms in an optical trap and have studied the lifetime of the gas as a function of magnetic field. At a field of 960 Gauss, where the three two-body scattering lengths are all large and negative, we have created a quantum degenerate Fermi gas of three coexisting states at a density $\simeq 10^{12}\mathrm{cm}^{-3}$ and found that the gas has a lifetime of several hundred milliseconds. The lifetime is shorter near the Feshbach resonances but is longer near the zero-crossings of the scattering lengths. We will report on our experimental progress and discuss prospects for future studies of spin-1 Fermi gases in the weak and strong coupling regimes.

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Monte Carlo simulation of an inhomogeneous two-component p-wave interacting Fermi gas

L. Rosales-Zárate, G. Toledo Sánchez, R. Jáuregui

Departamento de Física Teórica, Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, México 01000 D.F. México

Interactions between atoms can be controlled experimentally in ultracold Fermi gases via Feshbach resonances. This has increased the theoretical and experimental studies on the crossover between the BCS and the BEC regime in the s-wave channel. The scattering in this channel is isotropic in space, and the scattering length is the parameter that determine the main physical properties of the system. Recently, p-wave Feshbach resonances have been achieved experimentally [1], bringing the study of degenerate atomic gases in this channel to be a compelling issue. The p-wave scattering is anisotropic and the degeneracy of the angular momentum projection m_ℓ allows the possibility of multiple superfluid states, and phase transitions between those states[2]. Experimentally[1], for a single component Fermi gas, it is found that the p-wave Feshbach resonance energy splits depending on the values of m_ℓ. Besides, depending on the value of magnetic field, a metastable state with well defined energy may exist.

In this work, we study a system of two component Fermi atoms interacting through a p-wave channel and confined by a harmonic trap. The interacting potential is of short range and isotropic. This study is based on a comprehensive analysis of the two body problem from which the many body variational wave functions are constructed. For the two body problem, eigenfunctions and eigenenergies are evaluated on both sides of the unitarity limit where the volume of resonance $\mathcal{V}_s$ is divergent. For $\mathcal{V}_s < 0$, metastable states and dimers are observed. In the unitary limit and as the range of the potential tends to zero, the ground state energy eigenvalue is $0.71\hbar\omega$. Trial many body eigenfunctions are selected using a variational Monte-Carlo simulation up to 112 particles for the system ground state. The corresponding many body energies and space distributions are reported. A comparison with analogous results for s-wave interactions is also performed[3].

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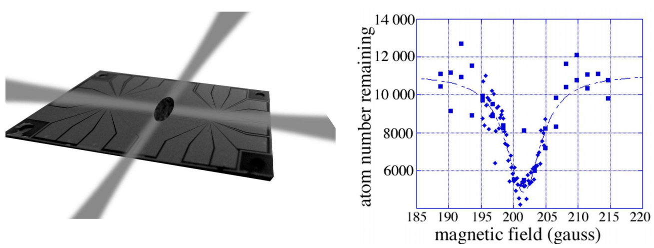
Many-body physics with ultracold atomic fermions

L. J. LeBlanc, M. H. T. Extavour, A. B. Bardon, D. M. Jervis, J. McKeever, J. H. Thywissen

IOS, CQIQC, and Department of Physics, University of Toronto, Canada

Superfluidity and magnetism are two phenomena which arise in condensed matter physics due to interactions between electrons. In systems of strongly interacting neutral fermions, superfluidity has been demonstrated in the regime of attractive interactions[1,2,3] and magnetism has been predicted in the regime of repulsive interactions[4].

We plan to use neutral ^{40}K atoms to study the physics of strong interactions among fermions, particularly in the regime of repulsive interactions. Currently, we simultaneously laser cool ^{87}Rb (a boson) and ^{40}K (a fermion) in a magneto-optical trap. We magnetically trap both species and transfer them to a microelectromagnetic chip trap. Here, the ^{87}Rb undergoes forced evaporative cooling while the ^{40}K is sympathetically cooled. The cold atoms are transfered to a far-off resonant optical dipole trap overlapping the magnetic trap formed by the chip. We have recently demonstrated the ability to manipulate the spin states of the atoms using high frequency radio waves and microwaves. We have also verified the presence[5] of a Feshbach resonance at 201 G through the observation of loss of atoms from the trap as a function of magnetic field strength. We are working towards the stabilization of our magnetic field for precise determination of the interaction strength and plan to use this to study the effects of interactions near resonance.



(a) (b)

Figure : *(a) Schematic of trapping configuration: atoms are transfered from a chip trap to a crossed-beam optical dipole trap; (b) Atom loss in a mixture of ^{40}K atoms in states $|F = 9/2, m_F = -9/2\rangle$ and $|F = 9/2, m_F = -7/2\rangle$ due to three-body collisions near the Feshbach resonance.*

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Mixture of a Spin-Polarized Fermi Gas in a box

L. M. Meléndez Rosales, V. M. Romero-Rochín

Instituto de Física, Universidad Nacional Autónoma de México, México
Apartado Postal $20 - 364$, 01000 *México, México D.F.*

We obtain various physical quantities using the mean-field approximation for a weakly interacting Fermi gas with an imbalance population. Beginning with a proposal of the ground state formed using states of two particles with momentum nonzero but definite is possible to arrive to equations BCS-like and from these obtain physical information like the gap equation and the chemical potentials.

Feshbach Resonances in Ultracold Lithium Rubidium Mixtures

C. Marzok, B. Deh, Ph. W. Courteille, C. Zimmermann

Physikalisches Institut der Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany

Ultracold atomic gases are a versatile instrument allowing to study the extremely rich field of many body physics with unprecedented control. Only a few parameters, namely temperature, atomic mass and interaction strength, govern the complex dynamics. In ultracold gases, these interactions are ruled by the s-wave scattering length. Control over this parameter is provided by magnetic Feshbach resonances. The physics involved can be enriched by choosing a mixture of different atomic species with different masses and/or different quantum statistics, e.g. Fermi-Bose or Bose-Bose mixtures. The $^{6/7}$Li-^{87}Rb systems are remarkable among these because of their large mass differences raising the question whether Born-Oppenheimer effects become measurable. Heteronuclear LiRb ground state molecules are predicted to have large permanent electric dipole moments, thus introducing strong anisotropic long-range interactions. Furthermore, very rich quantum phase diagrams are predicted for heteronuclear mixtures in 3d optical lattices. In order to be able to explore this remarkable range of systems, control over the interaction strength is needed.

We performed searches for heteronuclear Feshbach resonances in both the ^{6}Li-^{87}Rb (Fermi-Bose) as well as the ^{7}Li-^{87}Rb (Bose-Bose) mixture. For ^{6}Li-^{87}Rb, two resonances were found in the absolute ground state mixture $|F, m_F, F', m_{F'}\rangle = |1/2, +1/2, 1, +1\rangle$ [1] while five resonances were found for ^{7}Li-^{87}Rb $|F, m_F, F', m_{F'}\rangle = |1, +1, 1, +1\rangle$. This will allow for the precise determination of molecular potential parameters governing the crossing points of open and closed channels. The characterization of the observed resonances along with measurements of three-body decay rates are presented. Further, catalytic enhancement of the pure ^{6}Li p-wave resonance at $B = 158.5$ G could be observed in the presence of ^{87}Rb.

The control of interactions now available make these systems ideal candidates to study interaction induced phenomena for Bose-Fermi/Bose-Bose mixtures with large mass ratio where the Born-Oppenheimer approximation becomes increasingly important.

Recently, we also performed Bragg scattering of a spin-polarized ^{6}Li Fermi gas from a moving optical lattice demonstrating the controlled preparation of extremely long-lived non-equilibrium momentum states for interferometric purposes [2]. A section of this poster is devoted to these experiments showing the superiority of fermions for classical as well as matter wave atom interferometry over bosons. Very interesting prospects for the future application of this technique involve studying the coupling process in the BEC/BCS crossover regime[3] as well as studying resonance shifts due to interactions in the ^{6}Li-^{87}Rb Fermi-Bose mixture close to one of the discovered Feshbach resonances.

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BEC-BCS Crossover in ultracold ^{6}Li Fermi gas : a new experimental setup

N. Navon[1], S. Nascimbène[1], L. Tarruell[1], M. Teichmann[1], G. Duffy[1], J. McKeever[1,2], F. Chevy[1], C. Salomon[1]

[1]*Laboratoire Kastler-Brossel, Ecole Normale Supérieure, Paris, France*
[2]*Department of Physics, University of Toronto, Ontario, M5S 1A7, Canada*

The production and study of ultracold Fermi gases has attracted considerable effort, both experimentally and theoretically in the last few years. The realization of the first ultra-cold fermionic superfluids have been achieved using a Feshbach resonance, to tune the interactions between the fermions[1]. On one side of the resonance, a gas of weakly interacting Cooper pairs can form a BCS-type superconducting phase. On the other, the production of bosonic dimers can lead to molecular Bose-Einstein condensates. In between these two regimes, the gas is said to be in the strongly interacting regime where theoretical descriptions require beyond mean-field methods.

In the first part of the poster, we will briefly show the results that have been obtained on the previous experimental setup. In particular, the expansion of the ^{6}Li gas has been done in two different ways. First, interaction-free expansion gives direct measurement of the momentum distributions of the atomic cloud. This data can be simply compared with BEC-BCS crossover theories[2]. Secondly, if the interaction are kept on during the expansion, the released energy can be extracted from the size of the cloud. In this way, the universal factor relating the chemical potential to the Fermi energy at the Feshbach resonance has been measured experimentally.

In the second part of the poster, we will present the building of a next generation experimental setup, which uses bosonic ^{7}Li to sympathetically cool fermionic ^{6}Li. From a two species magneto-optical trap, we magnetically transport the gas to a Ioffe-Pritchard trap where we perform Doppler cooling. Evaporative cooling brings more than 10^7 atoms to a temperature of $80\ \mu$K, sufficiently low to achieve 100 $\%$ transfer efficiency into an optical dipole trap. We will present the latest performance of our setup, which already includes a ten-fold improvement of atom number comparing to our previous experiment. This setup will be upgraded with an optical lattice, in order to experimentally study model hamiltonians of condensed matter physics[3].

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Population Imbalanced Two-component Fermi Superfluidity inside Box-shape Trap: Self-consistent Calculations of $T = 0$ BdG Equation

M. Machida[1,2], T. Kano[1], M. Okumura[1,2], N. Nakai[1,2], N. Hayashi[1,2]

[1]*CCSE, Japan Atomic Energy Agency, 6–9–3 Higashi-Ueno, Taito-ku, Tokyo 110–0015, Japan*
[2]*CREST (JST), 4–1–8 Honcho, Kawaguchi, Saitama 332–0012, Japan*

Recently, two-component fermion systems with population imbalance have attracted much attention in various research fields, such as cold atoms, superconductors, and QCD. In the 1960's, effects of the population imbalance have been theoretically investigated in the superconductivity literature. Sarma considered the stability of the gapless phase (Sarma state)[1] and Liu and Wilczek revisited it with a new picture (interior gap phase)[2]. On the other hand, Fulde and Ferrell, and Larkin and Ovchinikov predicted the so-called FFLO state[3], where the superconducting order parameter is spatially modulated. Very recently, some evidence of the FFLO state has been reported in a heavy fermion superconductor.

The population imbalance has been also extensively studied in ultra-cold Fermi gases as well as superconductors. The advantage of using atom gases is that one can widely tune some physical parameters, such as the interaction and the population imbalance. However, in a trapped two-component ^{6}Li Fermi gas[4], a phase separation between a superfluid core region and a surrounding unpaired gas of excess atoms was clearly observed, while the exotic phases described above were not directly confirmed. We attribute the reason to the trap shape as a harmonic well, which brings inhomogeneities in particle density profiles. In fact, the stability of exotic phases in the presence of inhomogeneities has been a very complicated issue.

In this paper, we therefore suggest that a box shape trap is useful for an exploration of the above exotic phases. The box shape avoids non-significant spatial inhomogeneities and reveals intrinsic phases due to the population imbalance. We numerically solve the Bogoliubov–de Gennes Equations for two-component fermi atom gases with an open boundary condition and clarify which type of exotic phases emerges depending on the interaction strength.

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[4]M. W. Zwierlein, A. Schirotzek, C. H. Schunck, and W. Ketterle, Science **311**, 492 (2006); M. W. Zwierlein, A. Schirotzek, C. H. Schunck, and W. Ketterle, Nature **442**, 54 (2006); Y. Shin, M. W. Zwierlein, C. H. Schunck, A. Schirotzek, and W. Ketterle, Phys. Rev. Lett. **97**, 030401 (2006); G. B. Partridge, W. Li, R. I. Kamar, Y. A. Liao, and R. G. Hulet, Science**311**, 503 (2006); G. B. Partridge, W. Li, R. G. Hulet, M. Haque, and H. T. C. Stoof, Phys. Rev. Lett. **97**, 190407 (2006); C. H. Schunck, Y. Shin, A. Schirotzek, M. W. Zwierlein, and W. Ketterle, Science **316**, 867 (2007).

Large Wave Mechanical Simulations of Interacting Fermi Atoms

T. E. Judd, R. G. Scott, T. M. Fromhold

School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, UK

In spite of intense interest in cold Fermi atoms, little theoretical work has focused on the collective time-dependent wave mechanics[1]. This is primarily due to the major computer resources required and a lack of suitable models in the strongly interacting regime. We have used a quantum wave approach, based on a model Hamiltonian and implemented on high performance computers, to develop a new beyond-mean-field description of a two component gas of 128 Lithium-6 atoms. We have also explored the consequences of pushing our model system towards the strongly interacting regime. Despite the simplicity of the model, the results seem to capture features of the behavior observed in experiments close to the BEC-BCS crossover, including condensate fractions (see Fig. 1) and critical behavior observed in the strong BCS regime[2,3]. The simulations may provide new tools for understanding the underlying microscopic behavior of such gases.

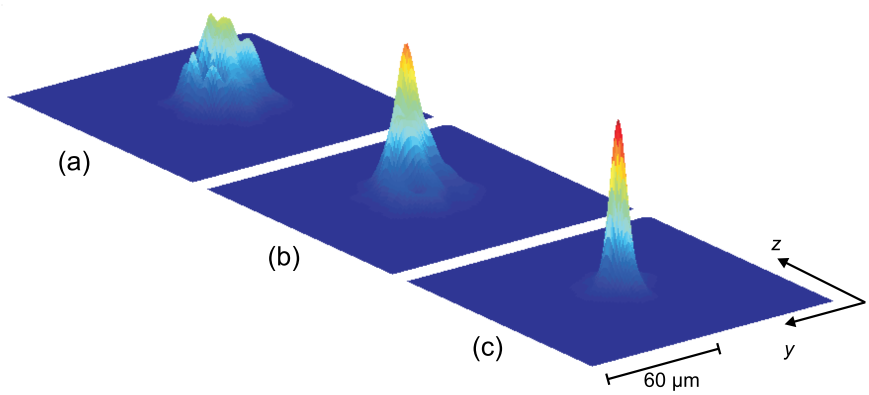

Figure 1: *Simulated density profiles of a two-component* ^{6}*Li gas undergoing evaporative cooling with strong interactions.*

[1]S. Giorgini, L. P. Pitaevskii and S. Stringari, arXiv:0706.3360v1 (2007)
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[3]L. Tarruell *et al.*, arXiv:0701181v1 (2007)

Towards a Finite Ensemble of Ultracold Fermions

S. Jochim[1,2], T. B. Ottenstein[1], T. Lompe[1], M. Kohnen[1], A. N. Wenz[1], G. Zürn[1]

[1] *Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany*
[2] *Ruprecht-Karls-Universität, Heidelberg, Germany*

During the past years, stunning experiments could be performed with strongly interacting Fermi gases. As an example, the crossover from a Bose-Einstein condensate of molecules to a gas of weakly bound BCS-like Cooper pairs could be studied in great detail. For all of those experiments the number of trapped particles was so large that their physics can be described in the thermodynamic limit. The techniques that have been developed for large Fermi Seas now make it seem feasible to also create ultracold ensembles that contain only very few atoms. The physics of such gases changes dramatically when the particle number becomes finite: Just as an example, a simple excitation gap will evolve into a whole spectrum of excitation levels.

To investigate these finite systems experimentally, all the energies of interest, such as the chemical potential or the excitation spectrum have to be in an observable range. Furthermore, the temperature has to be low enough that the thermal energy is well below those energy scales. Such parameters can be readily achieved by confining the atoms in a microtrap only a few cubic micrometers in size, which can be achieved in the tight focus of a laser beam.

As a well-established starting point for further experiments, we start from a molecular Bose-Einstein condensate of fermionic lithium atoms. Our setup and procedure is similar to the one described in [1]. In our new apparatus we can produce a BEC containing 2×10^5 molecules every 3 s, which is an essential starting point for all our future experiments.

Currently, we are preparing the setup for a tightly focused optical microtrap and high-resolution imaging. The molecular condensate will be transferred into the microtrap and converted into an extremely cold Fermi Sea of atoms. An important challenge will be to prepare a state with a defined number of atoms. The major idea and motivation for carrying out these experiments is that it should be possible to lower the microtrap potential in such a controlled way that only a precise number of quantum states will be left in the trap that should each be occupied with a single fermion, if the temperature of the gas is low enough.

Progress towards these goals will be reported.

[1] S. Jochim et al., Science 302, 2101

Effect of disorder on one-dimensional fermions in an optical lattice

B. Tanatar[1], G. Xianlong[2], M. Polini[3], M. P. Tosi[3]

[1] *Department of Physics, Bilkent University, Bilkent, 06600, Ankara, Turkey*
[2] *Physics Department, Zhejiang Normal University, Jinhua, 321004, China*
[3] *NEST-CNR-INFM and Scuola Normale Superiore, I-56126 Pisa, Italy*

Interacting two-component Fermi gases loaded in a one-dimensional (1D) lattice and subjected to an harmonic trapping potential exhibit interesting compound phases in which fluid regions coexist with local Mott-insulator and/or band-insulator regions. Motivated by experiments on cold atoms inside disordered optical lattices, we present a theoretical study of the effects of a correlated random potential on these ground-state phases. We employ a latttice version of density-functional theory within the local-density approximation to determine the density distribution of fermions in these phases. The exchange-correlation potential is obtained from the Lieb-Wu exact solution of Fermi-Hubbard model. On-site disorder (with and without Gaussian correlations) and harmonic trap are treated as external potentials. We find that disorder has two main effects: (i) it destroys the local insulating regions if it is sufficiently strong compared with the on-site atom-atom repulsion, and (ii) it induces an anomaly in the compressibility at low density from quenching of percolation. For sufficiently large disorder correlation length the enhancement in the inverse compressibility diminishes.

An ultracold fermion mixture of ^{6}Li and ^{40}K

T. G. Tiecke[1], A. Ludewig[1], S. Kraft[1], S. D. Gensemer[1,2], J. T. M. Walraven[1]

[1]*Van der Waals - Zeeman Institute - University of Amsterdam, The Netherlands*
[2]*Department of Physics, The Pennsylvania State University, USA*

We report on the creation of an ultracold mixture of the fermionic alkalis ^{6}Li and ^{40}K in an optical dipole trap. In the same trap we realized a three-component degenerate spin mixture of ^{40}K. To create the mixtures we start by loading a two-species magneto-optical trap (MOT) from two separate 2D-MOT sources. This is the first time a 2D-MOT source is realized for lithium. The source is clean, cold (30 m/s) and yields 3D-MOT loading rates of up to 10^{9} ^{6}Li atoms/s. The mixtures are captured in an optically-plugged magnetic quadrupole trap. The plug is realized with a 10 W Verdi (532nm) focused to a 14 micron waist. After forced evaporative cooling on the F=9/2-F=7/2 hyperfine transition of ^{40}K to a temperature of 10μK the ^{6}Li-^{40}K mixture can be loaded in the optical dipole trap. The lithium temperature follows by sympathetic cooling. Thus far we realized degenerate spin mixtures of $\sim 10^{5}$ ^{40}K-atoms at T = 0.3(1)T_F. For the dipole trap we use a 5 W IPG fiber laser (1070 nm) focused to a 20 micron waist. By translating the dipole trap focus we have transported, without significant losses, an ultracold sample of ^{40}K over a distance of 16cm into a science cell.

Preparation of a three-component degenerate Fermi gas

T. B. Ottenstein[1], T. Lompe[1], M. Kohnen[1], A. N. Wenz[1], G. Zürn[1], S. Jochim[1,2]

[1]*Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany*
[2]*Ruprecht-Karls-Universität, Heidelberg, Germany*

We report on the preparation of a three-component degenerate Fermi gas consisting of a balanced mixture of atoms in three different hyperfine states of ^{6}Li.[1] Due to wide and overlapping Feshbach resonances this new system offers the unique opportunity to tune the two-body scattering lengths over a wide range. This should make it possible to study phenomena like pairing competition, where two species pair up while the other one remains a spectator, or possibly the formation of trimers which is related to the formation of baryons in QCD.
We are able to prepare stable samples of $5 \cdot 10^4$ atoms per spin state at a temperature of 215 nK corresponding to 0.37 T/T_F. In the regime where all scattering lengths are small, we observe lifetimes exceeding 30 s. In a first experiment we studied the collisional stability of the gas for various magnetic field values between 0 and 600 G. From lifetime measurements we deduced three-body loss coefficients which show a strong dependence on the magnetic field. Most prominent is a strong loss feature at 130 G, which is not yet explained.

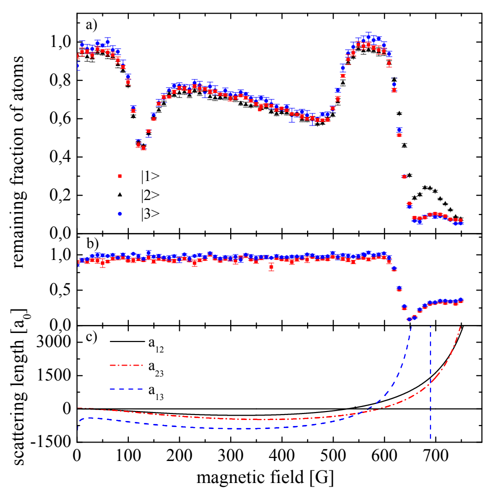


Figure 1: *a) Fraction of atoms remaining in the trap after holding the three-state mixture for 250 ms vs. magnetic field. b) Same measurement for a two-state mixture. Up to the region of the two-body Feshbach resonance the mixture is stable. c) Two-body scattering lengths for all particle combinations.*

[1]arXiv:0806.0587v1

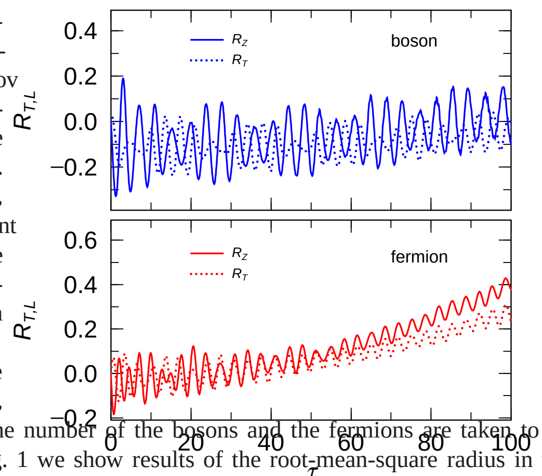
Quadrupole Oscillation in the Bose-Fermi Mixtures in the Time-Dependent Approach

T. Maruyama[1], H. Yabu[2]

[1] *College of Bioresouce Sciences, Nihon University, Fujisawa, Japan*
[2] *Department of Physics, Ritsumei-kan University, Japan*

Over the last several years, there have been significant progresses in the production of ultracold gases. degenerate atomic Fermi gases. In particular the Bose-Fermi (BF) mixing gases attract physical interest as a typical example in which particles obeying different statistics are intermingled. The spectrum of the collective excitations is an important diagnostic signal for these systems. Such oscillations are common to a variety of many-particle systems and are often sensitive to the interaction and the structure of the ground state and the excited states.

We study the collective monopole motion [1] and dipole motion [2] of the BF mixture by solving the time-dependent Gross-Pitaevskii (TDGP) equation and the Vlasov equation. When the boson-fermion interaction is weak, RPA can also describe the above behaviors in early time stage [2]. When the interaction becomes stronger, however, our approach shows quite diffrent behaviors from RPA: fast damping of the fermion oscillation in the strongly repulsive interaction [1,2], and large expansion in the strongly attractive interaction.



In this work we calculate the quadrupole oscillations in the system ^{170}Yb-^{173}Yb, which are realized by Kyoto group. The number of the bosons and the fermions are taken to be $N_b = 10000$ and $N_f = 1000$. In Fig. 1 we show results of the root-mean-square radius in the axial direction (R_L) and that in the transverse direction for boson (upper panel) and fermion (lower panel) which are normalized by each root-mean-square radius. In this system the boson-fermion interaction is strongly attractive, and we see that the fermi gas is expanded. We will find that the intrinsic frequency of the fermion quadrupole oscillation is very close to the intinsic frequency of boson monopole oscillation. When the amplitude is large, the total angular momentum is much larger than $2\hbar$ and the quadrupole motion is mixed with the monopole motion and make resonance.

[1] T. Maruyama, H. Yabu and T. Suzuki, Phys. Rev. **A72**, 013609 (2005).
[2] T. Maruyama and G.F. Bertsch, Phys. Rev. **A**, in press.

Resolved-sideband cooling of a micromechanical oscillator

A. Schliesser, R. Rivière, G. Anetsberger, O. Arcizet, T. J. Kippenberg

Max-Planck-Institut für Quantenoptik, Garching, Germany

Recent experimental progress has revived the interest in the coupling of optical and mechanical degrees of freedom on a mesoscopic scale[1]. In particular, realistic prospects for the observation of quantum phenomena in such systems have stirred much activity and joint efforts among the communities of quantum optics, atomic physics and micro- and nanomechanical systems alike. One major block on the road to such ambitions aims are thermal fluctuations present in the mechanical degrees of freedom even in very cold cryogenic environments, due to their low eigenfrequencies (typically < 100 MHz) and poor isolation from the environment. As a solution, laser cooling of the mechanical mode below the bath temperature has been demonstrated by several groups recently[1]. Quantum treatment of this technique however shows that it is subject to the same limit as Doppler cooling in atomic physics.[2] Following the highly successful approach taken in atomic physics decades ago, we have developed and optimized toroidal silica microstructures amenable to optical resolved-sideband-cooling.[3] While the minimum occupation dictated by the Doppler limit is reduced to $\langle n \rangle \sim 10^{-4}$, independent monitoring of the mechanical motion at the very high sensitivity[4] of the order $10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ reveals occupation of $\langle n \rangle \sim 5900$, limited by laser noise and heating by the 300-K environment. Recent progress made with a 1.6-K cryogenic environment and low-noise lasers will be discussed.

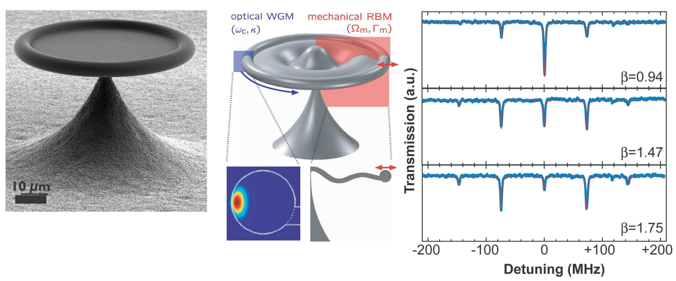


Figure 1: *Optomechanical coupling and resolved-sideband cooling. Electron micrograph (left) of toroidal silica microresonator used for cooling, supporting whispering-gallery modes in the toroid's rim and the mechanical radial breathing mode (center). The excited mechanical mode gives rise to optical absorption sidebands, which are much narrower than the mechanical eigenfrequency (right).*

[1] T. J. Kippenberg and K. J. Vahala, "Cavity Optomechanics," Optics Express **15**, 17172-17205 (2007)

[2] I. Wilson-Rae, N. Nooshi, W. Zwerger and T. J. Kippenberg, "Theory of Ground State Cooling of a Mechanical Oscillator Using Dynamical Backaction," Physical Review Letters **99**, 093901 (2007)

[3] A. Schliesser, R. Rivière, G. Anetsberger, O. Arcizet and T. J. Kippenberg, "Resolved-sideband cooling of a micromechanical oscillator," Nature Physics **4**, 415-419 (2008)

[4] A. Schliesser, G. Anetsberger, R. Rivière, O. Arcizet and T. J. Kippenberg, "High-sensitivity monitoring of micromechanical vibration using optical whispering gallery mode resonators," arXiv:0805.1608 (2008)

Demonstration of Ultra-Low Dissipation Optomechanical Resonators on a Chip

G. Anetsberger, R. Rivière, A. Schliesser, O. Arcizet, T. J. Kippenberg

Max-Planck-Institut für Quantenoptik, Garching, Germany

Dramatic progress in understanding and control of systems exhibiting coupling between optical and mesoscopic mechanical degrees of freedom has recently brought elusive opto-mechanical quantum effects closer to experimental reality than ever before.[1] The achievement of goals such as ground-state cooling, observation of quantum back-action or opto-mechanical squeezing, however, poses very stringent conditions on the optical and mechanical quality, but also on the optomechanical coupling in the candidate structure. In our experimental efforts at the MPQ, we employ toroidal silica whispering-gallery mode cavities, which exhibit very high finesse ($> 4 \cdot 10^5$) and strong optomechanical coupling to the mechanical radial breathing mode (RBM). To gain understanding of the limitations in the mechanical quality of the RBM, we have performed systematic measurements on mechanical resonance locations and quality factors while varying the geometry of the structure. This allows us to identify intermode coupling, with concomitant hybridisation and normal-mode splitting (“curve veering”), as the main source for mechanical dissipation in the RBM.[2] This finding is underpinned by finite-element modeling (FEM), which eventually allows us to quantitatively anticipate the mechanical quality from a numerically extracted parameter D. Microfabrication of an optimized virtual structure with strongly reduced clamping losses yields ultra-low dissipation room-temperature mechanical oscillators with $Q > 50,000$ at frequencies above 20 MHz. Limitations of the Q-factor by temperature-dependent intrinsic dissipation are discussed.

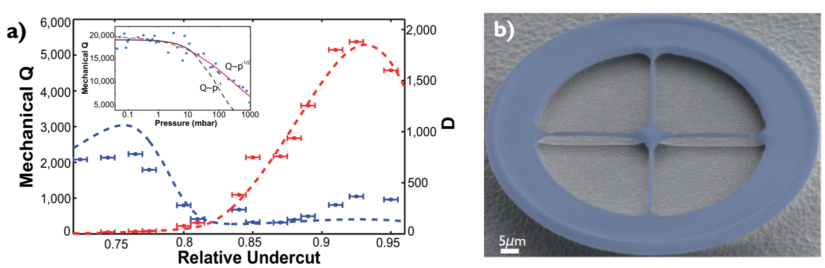


Figure 1: *Understanding and optimizing mechanical dissipation in silica microtoroids. (a) Measured quality factor (points) and simulated D-parameter (dashed lines) as a function of the undercut of the silica toroid. (b) Electron micrograph of an optimized device in which the toroid is supported by narrow spokes decoupling its motion from the central support.*

[1] T. J. Kippenberg and K. J. Vahala, “Cavity Optomechanics,” Optics Express **15**, 17172-17205 (2007)

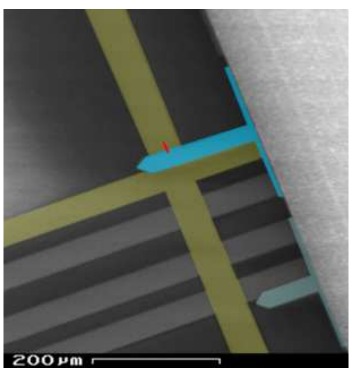
[2] G. Anetsberger, R. Rivière, A. Schliesser, O. Arcizet and T.J. Kippenberg, “Demonstration of Ultra Low Dissipation Optomechanical Resonators on a Chip,” arXiv:0802.4384 (2008)

Ultracold atoms coupled to micro- and nanomechanical resonators on an atom chip

D. Hunger[1,2], S. Camerer[1,2], T. W. Hänsch[1,2], J. Reichel[3], D. König[1], J. P. Kotthaus[1], P. Treutlein[1,2]

[1]*Department für Physik, Ludwig-Maximilians Universität, Munich, Germany*
[2]*Max-Planck-Institute of Quantum Optics, Garching, Germany*
[3]*Laboratoire Kastler Brossel, ENS, Paris, France*

The experimental fusion of quantum optical and condensed matter systems is a new, promising research field. In this context, atom chip experiments seem particularly well suited due to the high degree of control over atoms close to surfaces.
In our work we study the coupling of ultracold atoms to micro- and nanostructured mechanical resonators. As a first experimental step in this new field, we couple a BEC of ^{87}Rb atoms to the vibrations of an AFM cantilever. The coupling arises due to the Casimir-Polder surface potential. It leads to reduced depth and distortion of the magnetic trap, giving rise to atom loss and heating. We show experimental data where we use this to reveal the fundamental resonance of the AFM cantilever.



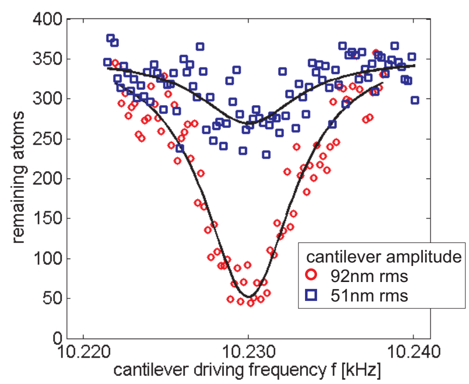


Figure 1: *Left: SEM picture of the AFM cantilever on a chip with gold wires for magnetic trapping. Right: Remaining atom number after* 7 *ms holding time at* 800 *nm distance from the cantilever surface for varying cantilever driving frequency.*

As a candidate for a hybrid quantum system, we propose to magnetically couple ultracold atoms to a nanomechanical cantilever with a ferromagnetic tip. The resonator vibrations cause an oscillating magnetic field that can drive atomic spin-flip transitions. At room temperature this can be used to probe the thermal motion of the cantilever with the atoms. Theoretical investigations show that for low temperatures and high resonator Q-factors the back-action of the atoms onto the cantilever can be significant and the system represents a mechanical analog to cavity QED in the strong coupling regime.[1]

[1]P. Treutlein, D. Hunger, S. Camerer, T. W. Hänsch, and J. Reichel, PRL **99**, 140403 (2007).

Schrödinger cat states in rotating ultra-cold atoms

D. W. Hallwood[1,2], J. A. Dunningham[2]

[1]*Clarendon Lab., University of Oxford, Parks Road, Oxford, OX1 3PU, UK*
[2]*School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK*

Dilute gases of ultra-cold atoms provide an ideal quantum-many body system for studying macroscopic quantum phenomena. They can be trapped and manipulated using optical and magnetic fields and their interactions are well understood. This means that they can be modelled theoretically starting from the level of single particles unlike other condensed matter systems, which are limited to a collective quantum variable description.
Our work investigates macroscopic quantum superpositions (cat states) of ultra-cold atoms in a loop split by one or more potential barriers. We have developed two schemes that create superpositions of single modes of quasi-momentum (or superfluid flow). The first involves non-adiabatically ramping up the barriers, allowing evolution for a fixed time, then non-adiabatically lowering them again[1]; the second involves applying a π phase around the loop when the barriers are low[2]. The applied phase acts as an effective magnetic field and can be generated by rotating the system or by transferring orbital angular momentum from Laguerre-Gaussian photons to each atom.
To create superposition the single mode states must be near degenerate, there must be strong coupling between them, and the coupling to other states must be weak. We show that these requirements become harder to satisfy as the system size increases, so providing three reasons (other than decoherence) why cat states are difficult to generate[3]. Recent work investigates how these requirements can be satisfied for larger numbers of particles.
This work not only gives further insight into our understanding of the transition from quantum to classical physics, but the system may also be useful in a range of quantum information and precision measurement schemes.

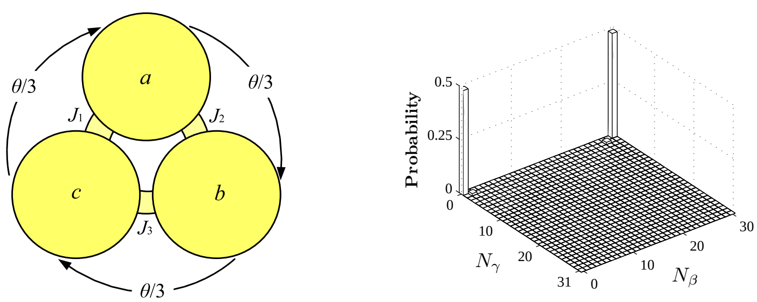


Figure 1: *LEFT: System for creating superpositions of flow. A phase, ϕ, can be applied around the loop, atoms can interact on a site and tunnel between sites with strength J_i. RIGHT: Figure shows a superposition of states $|30,0,0\rangle_{\alpha\beta\gamma}$ and $|0,30,0\rangle_{\alpha\beta\gamma}$.*

[1]J.A. Dunningham, D.W. Hallwood, Phys. Rev. A **74** 023601 (2006).
[2]D.W. Hallwood, et al. New J. Phys. **8** 180 (2006).
[3]D.W. Hallwood, et al. J. Mod. Opt. **54** 2129 (2007)

Mesoscopic Dipolar Crystals of Rydberg-Dressed Atoms

G. Pupillo[1,2], I. Lesanovsky[1,2], A. Micheli[1,2], P. Zoller[1,2]

[1]*Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria*
[2]*Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria*

We discuss the possibility of observing mesoscopic self-assembled crystals in a gas of ultracold neutral alkali atoms. The electronic ground state is weakly coupled to a Rydberg Stark-state by an off-resonant laser thus acquiring a permanent electric dipole moment which is of the order of a few Debye. Starting from large mean interparticle distances the system undergoes a superfluid to crystal phase-transition as it is compressed. Under further compression a superfluid phase is re-established.

Non-equilibrium suppression of electron spin dephasing in quantum dots

M. Gullans[1], J. J. Krich[1], J. M. Taylor[1,3], B. I. Halperin[1], A. Yacoby[1], M. Stopa[2], M. D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2]*Center for Nanoscale Systems, Harvard University, Cambridge, MA 02138, USA*
[3]*Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Recent experiments have investigated the controlled polarization of lattice nuclear spins in semiconductor quantum dots via the contact hyperfine interaction. We examine how such dynamical nuclear polarization (DNP) can lead to the emergence of novel non-equilibrium configurations of nuclear spins associated with "dark" spin states. Specifically, we develop a simplified model for DNP in these quantum dot systems and study the asymptotic nuclear spin dynamics that occur while DNP saturates. This analysis provides a theoretical basis for the observation of reduced Overhauser gradient magnetic fields, the so called "Zamboni" effect, which leads to a marked increase in the ensemble dephasing time, T_2^*, in such quantum dot systems. In addition, several experimental manifestations of these novel dark spin states role in DNP are predicted.

Improved Phonon QND Readout Using Degenerate Cavity Modes

J. C. Sankey, A. M. Jayich, B. M. Zwickl, C. Yang, J. G. E. Harris

Department of Physics, Yale University, 217 Prospect St., New Haven, CT 06511

Optomechanical devices in which a flexible SiN membrane is placed inside an optical cavity provide a means to achieve very high finesse and mechanical quality factor in a single device. They also provide fundamentally new functionality, notably that the cavity detuning can be a quadratic function of membrane position. This enables a measurement of position squared (x^2) and in principle a QND phonon number readout of the membrane. Using a single transverse mode, the readout sensitivity is far to low to observe single phonons. Here we demonstrate that we can realize much higher sensitivity using two nearly-degenerate transverse modes.

As shown in Fig. 1a, the cavity modes' detuning is a sinusoidal function of the membrane position. At each turning point the detuning is quadratic, enabling the single-mode x^2-readout. If the membrane is tilted relative to the cavity axis or displaced relative to the cavity waist, it breaks the cavity's symmetry and lifts the degeneracies apparent in Fig. 1a. Fig. 1b shows a close-up of the crossings between the singlet TEM$_{00}$ mode, and the triplet TEM$_{20,11,02}$ modes with the membrane intentionally misaligned to lift the triplet degeneracy. Between modes of the same transverse symmetry the crossings are avoided, and at these points the quadratic position dependence is ten times stronger than for a single mode.

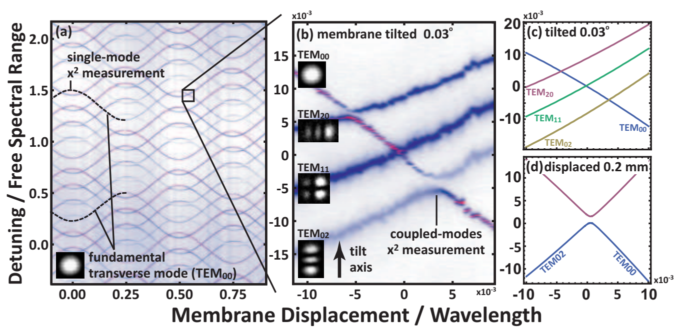


Figure 1: *(a) Cavity transmission coupled to many modes. (b) Singlet/triplet crossing. (c) Model, showing effect of tilt on triplet degeneracy. (d) Degenerate model.*

Modeling the membrane as a thin sheet perturbing the free-space wave equation we reproduce the degeneracy lifting and avoided crossing behavior, as shown in Fig. 1c-d. We find the size of the avoided gap is proportional to the membrane's distance from the cavity waist. Our calculations suggest that mm-scale control of the membrane's position should enable one to tune the x^2 readout strength over a very wide range.

Sagnac Effect in an Array of Electron Matter Wave Interferometers

John R.E. Toland, C. P. Search

Department of Physics and Engineering Physics,Stevens Institute of Technology, Hoboken NJ, 07030

The Sagnac effect is an important phase coherent effect in optical and atom interferometers where rotations of the interferometer with respect to an inertial reference frame result in a shift in the interference pattern proportional to the rotation rate. The Sagnac effect is in principle observable with other types of matter waves besides just atoms. Here we analyze for the first time the Sagnac effect in an array of mesoscopic electron interferometers. These interferometers consist of rings with a radius of $\sim 1\mu m$ connected in series. The electrons exhibit coherent ballistic transport through the ring segments [1] and incoherent transport in between the rings. Despite the small size of each ring, the cascaded array of such rings allows one to obtain an effective area that scales like $\sqrt{N}$ where N is the number of rings.
We include in our analysis the effects of various noise sources including Johnson-Nyquist and shot noise that degrade the sensitivity of the interferometer array. In this analysis we derive an analytic expression for the signal to noise ratio (SNR) that allows us to determine the number of rings needed to obtain a desired SNR for a specific operating temperature, rotation rate, and device bandwidth. We show that for SNR > 1 and rotation rates less than $2\pi s^{-1}$, the number of required rings is on the order of $10^3 - 10^4$, which is much less than the number of rings that could be accommodated in microfabricated structures. Our results indicate that an array of mesoscopic Sagnac electron interferometers are sensitive enough to measure rotation rates required for practical applications.

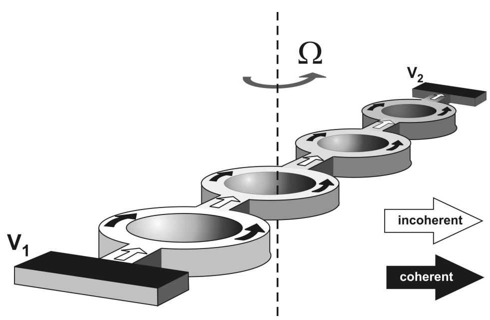


Figure 1: *An array of ring interferometers connected in series with a bias voltage $V_1 - V_2$. The electron beam is split as it enters the ring and a rotation, Ω, induces a path difference between the two beams resulting in phase shift proportional to Ω. The interference is measured in the total conductance of the array.*

[1] M. Zivkovic, M. Jääskelänen, C.P. Search, I. Djuric “Sagnac Rotational Phase Shifts in a Mesoscopic Electron Interferometer with Spin-Orbit Interactions”,Phys.Rev. B 77, 115306 (2008)

Cooling and detecting nanomechanical motion with a microwave cavity

C. A. Regal[1,2], J. D. Teufel[1], J. Harlow[1], K. W. Lehnert[1]

[1] *JILA, National Institute of Standards and Technology and the University of Colorado, and Department of Physics University of Colorado, Boulder, Colorado 80309, USA*
[2] *Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125*

With the advent of micro and nanoscale mechanical resonators, researchers are rapidly progressing toward a tangible harmonic oscillator whose motion requires a quantum description. Challenges include freezing out the thermomechanical motion to leave only zero-point quantum fluctuations and, equally importantly, realizing a Heisenberg-limited displacement detector. We have created a microwave detector of mechanical motion that can be in principle quantum limited and is also capable of efficiently coupling to the motion of small mass, nanoscale objects, which have the most accessible zero-point motion. Specifically we have measured the displacement of a nanomechanical beam using a superconducting transmission-line microwave cavity. We realize excellent mechanical force sensitivity (3 aN/$\sqrt{\mathrm{Hz}}$), detect thermal motion at 10's of milliKelvin temperatures, and achieve a displacement imprecision of 30 times the standard quantum limit.[1] In our most recent measurements we have observed damping and cooling effects on the mechanical oscillator due to the microwave radiation field in the resolved-sideband limit; these results complement the recent observation of such cooling effects in the optical domain. We discuss the prospects for employing this dynamical backaction technique to cool a mechanical mode entirely to its quantum ground state with microwaves.[2]

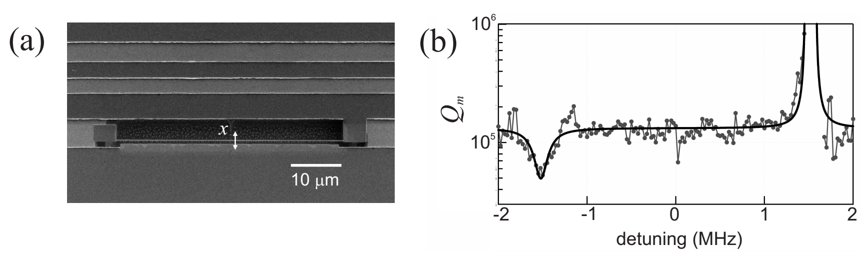


Figure 1: *(a) A nanomechanical beam embedded in a transmission-line microwave cavity. The beam motion in x capacitively couples to the cavity resonance frequency. (b) Effect of microwave radiation pressure on the mechanical quality factor as a function of microwave carrier detuning from the cavity resonance.*

[1] C. A. Regal, J. D. Teufel, and K. W. Lehnert, "Measuring nanomechanical motion with a microwave cavity interferometer" Nature Physics, doi: 10.1038/nphys974 (2008).
[2] J. D. Teufel, C. A. Regal, and K. W. Lehnert, "Prospects for cooling nanomechanical motion by coupling to a superconducting microwave resonator" arXiv:0803.4007v2 (2008).

Observation of Bogoliubov excitations in exciton-polariton condensates

S. Utsunomiya[1,2], L. Tian[3], G. Roumpos[3], C. W. Lai[1,3], N. Kumada[2], T. Fujisawa[2], M. Kuwata-Gonokami[4], A. Löffler[5], S. Höfling[5], A. Forchel[5], Y. Yamamoto[1,3]

[1]*National Institute of Informatics, Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan.*
[2]*NTT Basic Research Laboratories, NTT Corporation, Atsugi, Kanagawa 243-0198, Japan*
[3]*E.L.Ginzton Laboratory, Stanford University, Stanford, CA 94305-4088*
[4]*Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[6]*Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*

Exciton-polaritons in a semiconductor microcavity, which are elementary excitations created by strong coupling between quantum well excitons and microcavity photons, were proposed as a new Bose-Einstein condensation (BEC) candidate in solid state systems[1]. Recent experiments with exciton-polaritons demonstrated several interesting signatures from the view point of polariton condensation, such as, quantum degeneracy at nonequilibrium condition[2], polariton bunching effect at condensation threshold[3], long spatial coherence[4] and quantum degeneracy at equilibrium condition[5]. Einstein's 1925 paper predicted the occurrence of BEC in an ideal gas of non-interacting bosonic particles. However, the particle-particle interaction and the Bogoliubov excitation spectrum are at heart of BEC and superfluidity physics. The experimental verification of the Bogoliubov theory on the quantitative level was performed for atomic BEC[6] using two-photon Bragg scattering technique[7], but have only been studied theoretically for exciton-polaritons[8 9].

In this poster, we will present the first observation of the Bogoliubov excitation spectra and the five distinct features of particle-particle interaction in the polariton condensate: blue shift of the condensate energy U due to the interaction in the polariton condensate among particles in a condensate, increase in the condensate size due to the same origin, increase in the position-uncertainty product due to the same origin, phonon-like linear excitation spectrum at low momentum regimes and blue shift of the free particle energy $2U$ due to condensate-free particle interaction. The nonlinear behaviours of the condensate and excitations are in quantitative agreement with the Bogoliubov theory and numerical analysis based on Gross-Pitaevskii equation. In spite of the short lifetime and dynamical nature of the LP condensate, the Bogoliubov theory for interacting Bose gases has been demonstrated in this experiment.

[1]A. Imamoglu et al., Phys. Rev. A 53, 4250 (1996).
[2]L. S. Dang et al., Phys Rev Lett 81, 3920 (1998).
[3]H. Deng et al., Science 298, 199 (2002).
[4]H. Deng et al., Phys Rev Lett 99, 126403 (2007).
[5]H. Deng et al., Phys Rev Lett 97, 146402 (2006).
[6]M. H. Anderson et al., Science 269, 198 (1995).
[7]D. M. Stamper-Kurn et al., Phys Rev Lett 83, 2876 (1999).
[8]D. Sarchi, and V. Savona, Phys Rev B 77, 045304 (2008).
[9]I. A. Shelykh, G. Malpuech, and A. V. Kavokin, physica status solidi (a) 202, 2614 (2005).

'Trapped Rainbow' in Graphene

L. Zhao[1], S. F. Yelin[1,2]

[1] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[2] *ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*

We theoretically propose a method of coherent trapping quasiparticles in a sharp graphene p-n-p junction based on the so-called 'trapped rainbow'[1] technique. Our investigation indicates that, at a sharp p-n junction, the Dirac quasiparticles can undergo the total internal reflection and obtain a negative Goos-Hänchen-like shift. This shift plays an important role in the trapping process.

[1] Kosmas L. Tsakmakidis, Allan D. Boardman and Ortwin Hess, 'Trapped rainbow' storage of light in metamaterials, Nature(London), 450, 397-401 (2007)

Poster Session III

Thursday, July 31
4:15 pm – 6:00 pm
Wilbur Cross Building, Reading Rooms

Bose Gases

Cold Molecules

Trapped ions

Intense Fields and Ultrafast Phenomena

Other

Large magnetic storage ring and beamsplitter for BECs

M. Zawadzki, E. Riis, A. S. Arnold

SUPA, Dept. of Physics, University of Strathclyde, Glasgow G4 0NG, UK

Bose-Einstein condensates are stored in a $10\,\mathrm{cm}$ diameter vertically oriented magnetic ring trap.[1] After two revolutions in the ring the radial density distribution of the BEC is bimodal with the coolest (condensed) fraction having a fitted radial temperature of $10\,\mathrm{nK}$ and low loss propagation has been observed over a total distance of $\approx 2\,\mathrm{m}$. BECs at the exact top of the ring are split into two counter-rotating clouds which are recombined after one revolution. The ring is ideal for studying condensate collisions (at $1.4\,\mathrm{m/s}= 20\,\mathrm{mK}$) and Sagnac interferometry (the enclosed area is an integer multiple of $7200\,\mathrm{mm}^2$).

[1] A.S. Arnold, C.S. Garvie, and E. Riis, Phys. Rev. A 73, 041606(R), (2006).

Observation of a 2D Bose-gas: from thermal to quasi-condensate to superfluid

A. Ramanathan, P. Cladé, C. Ryu, K. Helmerson, W. D. Phillips

Joint Quantum Institute, University of Maryland and National Institute of Standards and Technology, Gaithersburg MD 20899-8424

We present experimental results on a Bose gas in the quasi-2D geometry near the Berezinskii, Kosterlitz and Thouless (BKT) transition temperature. By measuring the density profile, in situ and after time of flight, and the coherence length of the gas, we identify different states of the gas. In particular, we observe that the gas develops a bimodal distribution without long range order, which we identify as the quasi-condensed non-superfluid phase. In this state, the gas presents a longer coherence length than the thermal cloud, but shorter than that of the superfluid. Experimental evidence seems to indicate that we also observe the transition towards superfluidity (BKT transition), where we observe a clear discontinuity in the rate of change of the width of the narrow peak for short time-of-flight and the sudden appearance of a trimodal distribution at long time of flight.

Theory of Bose-Einstein condensate interferometry

B. J. Dalton

ARC Centre for Quantum-Atom Optics and Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne, Victoria 3122, Australia

Bose-Einstein condensates (BEC) in cold atomic gases are a quantum system on a macroscopic scale. At near zero temperature essentially all bosons occupy a small number of single particle modes – in the simplest situations only one mode. Interferometry using BECs (such as splitting a trapped BEC into two traps and then recombining the BECs) offers a possible precision improvement given by the square root of the boson number. For non-interacting bosons and isolated BECs, the quantum correlation functions [1] describing interference experiments display clear interferometric effects. However, even for isolated BECs, internal boson-boson interactions can still result in de-phasing (associated with transitions within condensate modes) and decoherence effects (associated with transitions out of condensate modes) that degrade the interference pattern.

A theory of decoherence and dephasing effects has been developed for BEC interferometry using a phase space method where the density operator is represented by a phase space distribution functional [2], with highly occupied condensate modes described via the Wigner representation and the basically unoccupied non-condensate modes via the positive P representation [3] [4]. The theory has now been generalised to apply to an interferometry regime where up to two condensate modes can have a macroscopic occupancy, as may occur in double-well BEC interferometry. A mean field theory for treating dephasing effects based on a two-mode approximation [5] has previously been developed, leading to generalised coupled Gross-Pitaevskii equations for the mode functions. For the new phase space treatment allowing also for decoherence effects, Ito stochastic equations for condensate and non-condensate fields have been obtained from Fokker-Planck equations for the distribution functional after applying truncation approximations. Stochastic averages then give the quantum correlation functions.

[1] R. Bach and K. Rzazewski, "Correlation functions of cold bosons in an optical lattice", Phys. Rev. A 70, 063622 (2004).

[2] M. J. Steel, M. K. Olsen, L. I. Plimak et al, "Dynamical quantum noise in trapped BECs", Phys. Rev. A 58, 4824 (1998).

[3] B. J. Dalton, "Theory of Decoherence in Bose-Einstein Condensate Interferometry", J. Phys: Conference Series 67, 012059 (2007).

[4] S. E. Hoffmann, J. F. Corney and P. D. Drummond, "Hybrid phase-space simulation method for interacting Bose fields", In Press, Phys. Rev. A.

[5] B. J. Dalton, "Two-Mode Theory of Bose-Einstein Condensate Interferometry", J. Mod. Opt. 54, 615 (2007).

All-optical production of chromium Bose-Einstein Condensates.

B. Laburthe-Tolra, Q. Beaufils, R. Chicireanu, T. Zanon, E. Maréchal, L. Vernac, J. C. Keller, O. Gorceix

Laboratoire de Physique des Lasers, CNRS UMR 7538, Université Paris 13, 99 Avenue J.-B. Clément, 93430 Villetaneuse, France

We report on Bose-Einstein condensation of chromium atoms in a crossed optical-dipole trap. This achievement should allow us to study the effect of large dipole-dipole interactions in the Bose-Einstein condensate (BEC), related to the large magnetic moment of Cr atoms. In our experiment, both ^{52}Cr and ^{53}Cr atoms can be simultaneously cooled and trapped [1]. To reach BEC with ^{52}Cr, we first accumulate ^{52}Cr atoms in an optical dipole trap from a magneto-optical trap. To limit light-assisted collisions, we optically pump the atoms into metastable states during the loading of the trap. To optimize the loading, and to trap all Zeeman states, we apply fast radio-frequency sweeps to the atoms, so that their spin state alternates between opposite values. This averages out magnetic forces acting on the atoms[2], which improves the loading rate by a factor of roughly 5. We then repump the atoms to their absolute ground state, and perform evaporative cooling in a crossed optical dipole trap, to reach Bose-Einstein condensation after 14 s[3].

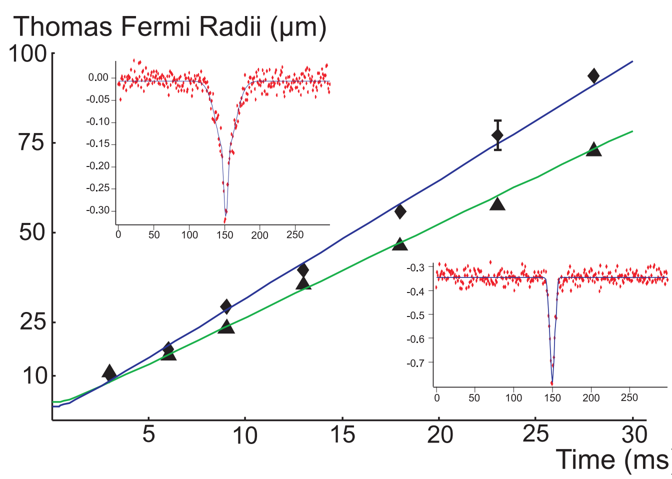


Figure 1: *Evidence for BEC. We show the ballistic anisotropic expansion of the BEC after it is released from the trap, as well as two cuts through absorption images, showing (1) a bimodal distribution at 150 nK and (2) a pure BEC (at en even colder temperature).*

[1]R. Chicireanu et al., Phys. Rev. A, **73**, 053406 (2006).
[2]Q. Beaufils et al., Phys. Rev. A , **77** , 053413 (2008)
[3]Q. Beaufils, et al., Phys. Rev. A **77**, 061601(R) (2008)

Quasi-2D Bose Einstein condensation of Cooper pairs and high T_c superconductivity

C. Villarreal[1], M. de Llano[2]

[1]*Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, 04510, Mexico*
[2]*Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México, Mexico City, 04510, Mexico*

Cuprate superconductors comprise layered structures involving buckled CuO_2 planes separated by a relatively large distance $\sim 12\,A$ along the c axis. It is generally accepted that superconductivity takes place within the Cu and O planes, a short distance $\sim 0.2\,A$ apart. Although high T_c superconductors share many characteristics common to normal superconductors, it is not clear whether a BCS theory is satisfactory to explain the main differences such as their high critical temperature, or their short coherence length $\sim 10\,A$.
We propose that high-T_c superconductivity in cuprate materials may be described by means of a Bose-Einstein condensate of excited Cooper pairs constrained to propagate within quasi-2D layers of $finite\ width\ \delta$ defined by the CuO_2 planes. With that purpose, the problem of Bose-Einstein condensation is studied for low-dimensional systems satisfying a linear energy-momentum dispersion relation. Thermodynamic quantities such as number density, energy density, specific heat, and critical temperature (T_c) are evaluated as a function of δ. We show that $T_c^2 \propto \delta n_s$, being n_s the condensate density, consistently with recent experimental findings in severely underdoped cuprate materials. Furthermore, for atomic layer widths $\sim 1\,A$, a critical temperature $T_c \sim 100$ K is obtained.

Bragg scattering from a Bose-Einstein condensate near a Feshbach resonance

C. Sahlberg, R. J. Ballagh, C. W. Gardiner

Jack Dodd Centre for Photonics and Ultra-Cold Atoms, Department of Physics, University of Otago, P.O. Box 56, Dunedin, New Zealand

Feshbach resonances have been used in a number of experiments to manipulate the inter-atomic interaction strength of bosonic atoms, and to partially convert atomic condensates into molecular condensates[1]. In a recent experiment, Papp et al.[2] have used Bragg spectroscopy to probe the behaviour of a strongly interacting Bose-Einstein condensate of ^{85}Rb, near the Feshbach resonance at 155 G. We present a theoretical model for Bragg scattering from a Bose-Einstein condensate in the vicinity of a magnetic Feshbach resonance. The model employs two fields, of which the first corresponds to atoms and the second corresponds to the pairing of atoms into molecules[3], and we tune the binding energy of the molecules to model the Feshbach resonance and the associated increase in the effective scattering length. We use a classical field Projected Gross-Pitaevskii formalism[4], and we discuss the relevance of our results in modelling the experiment of Papp et al..

[1] E. A. Donley, N. R. Claussen, S. T. Thompson and C. E. Wieman, Nature (London) **417**, 529 (2002)
[2] S. B. Papp, J. M. Pino, R. J. Wild, S. Ronen, C. E. Wieman, D. S. Jin and E. A. Cornell, arXiv:0805.0295v1.
[3] E. Timmermans, P. Tommasini, M. Hussein and A. Kerman, Phys. Rep. **315**, 199 (1999)
[4] P. B. Blakie and M. J. Davis, Phys. Rev. A **72**, 063608 (2005)

Numerical Investigation of Contrast Degradation of BEC Interferometer

Chien-Nan Liu[1], G. Gopi Krishna[2], Shinichi Watanabe[2]

[1]*Department of Physics, Fu-Jen Catholic University, Taipei 24205, Taiwan*
[2]*Department of Applied physics and Chemistry, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo 182-8585, Japan*

We use a single wave function description under the framework of the mean field approximation to study the dynamics of a split condensate in various types of atom interferometers using Bragg diffraction. Our goal is to explore ways to improve, or if possible, optimize the contrast of the interference signals. Two strategies are introduced to compensate for the relative shift in momenta or spatial displacement between the two recombining components due to the atomic interaction or the trapping potential by manipulating the recombination pulse. One is to introduce a time lag; the other is to introduce a frequency shift. We account for the degradation as well as the optimization of the contrast based on the wave function properties in both configuration and momentum spaces. In trapless situation, both schemes can improve the contrast in either a Mach-Zehnder (MZ) or Double-reflection (DR) interferometer[1]. In the presence of trapping, while a DR interferometer can not be fixed by either of the optimization schemes, a MZ interferometer can be improved only by the Δk scheme. In contrast, a dephasing-free interferometer[2] is very effective and the contrast of interference signal can be improved by either optimization schemes.

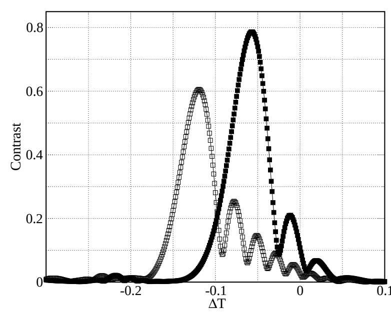


Figure 1: *The contrast of a MZ interferometer as a function of the time lag of the recombination Bragg pulse ΔT in the absence of trapping for two different atom numbers, N=3000 (solid square) and N=8000 (open square).*

[1]O. Garcia, B. Deissler, K. J. Hughes, J. M. Reeves, and C. A. Sackett, Phys. Rev. A **74**, 031601(R) (2006).
[2]M. Horikoshi and K. Nakagawa, Phys. Rev. Lett. **99**, 180401 (2008).

Yang-Yang Thermodynamics on an Atom Chip

A. H. van Amerongen[1], J. J. P. van Es[1], P. Wicke[1], K. V. Kheruntsyan[2], N. J. van Druten[1]

[1]*Van der Waals-Zeeman Instituut, Universiteit van Amsterdam, The Netherlands*
[2]*ARC Centre of Excellence for Quantum-Atom Optics, University of Queensland, Brisbane, Australia*

We investigate the behavior of a weakly interacting nearly one-dimensional (1D) trapped Bose gas at finite temperature.[1] The experiments employ a gas of ultracold ^{87}Rb atoms, magnetically trapped by a microfabricated current-carrying structure, an "atom chip". We perform in situ measurements of spatial density profiles and show that they are very well described by a model based on exact solutions obtained using the Yang-Yang thermodynamic formalism.[2] The comparison is done in a regime where other, approximate theoretical approaches fail. This constitutes the first direct comparison between experiments on the 1D Bose gas and theory based on the Yang-Yang exact solutions. Furthermore, we use Bose-gas focusing to probe the equilibrium axial momentum distribution of the gas, a quantity for which the Yang-Yang solutions do not yield a direct prediction. Our results establish a new and strong link between experiments on low-dimensional quantum gases and exact theory for interacting quantum many-body systems at finite temperature.

[1]A. H. van Amerongen et al., Phys. Rev. Lett. **100**, 090402 (2008)
[2]C. N. Yang and C. P. Yang, J. Math. Phys. (N.Y.) **10**, 1115 (1969)

Coherent modes excitation by modulation of interaction in a BEC

E. R. F. Ramos[1], E. A. L. Henn[1], J. A. Seman[1], M. Caracanhas[1], K. M. F. Magalhães[1], V. I. Yukalov[2], V. S. Bagnato[1]

[1] *Instituto de Física de São Carlos, Universidade de São Paulo, Caixa Postal 369, 13560-970, São Carlos-SP Brazil*
[2] *Bogolubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research Dubna 141980, Russia*

The coherent states of a trapped Bose-Einstein condensate (BEC) are described by the solutions to the Gross-Pitaevskii equation (GPE). To transfer BEC from the ground to a nonground state, it is necessary to apply a time-dependent perturbation, with the frequency close to the considered transition, as a result of which the resonantly excited condensate composes an effective two-level system. The external fields, considered in the previous works [1] were formed by spatially inhomogeneous alternating trapping potentials. In this work, we proposed a new technique for creating nonground-state BEC in a trapping potential by means of the temporal modulation of atomic interactions. The main idea is to superimpose onto the BEC an uniform magnetic field with a time variation of a small amplitude. Due to the Feshbach resonance effect, such oscillatory field creates an alternating modulation of the scattering length. We show that, due this modulation, it is possible to transfer coherently atoms from the ground to a chosen excited coherent state. It is also shown that there occurs a phase-transition-like behavior in the time-averaged population imbalance between the ground and excited states. The application of the suggested technique to realistic experimental conditions is analyzed and it is shown that the considered effect can be realized for experimentally available condensates.

[1] V.I. Yukalov, E.P. Yukalova, and V.S. Bagnato,Phys. Rev. A **56**, 4845 (1997); **66**, 043602 (2002).

Vortices formation by oscillatory excitation of a BEC

E. A. L. Henn[1], J. A. Seman[1], E. R. F. Ramos[1], M. Caracanhas[1], E. P. Olimpio[1], P. Castilho[1], G. Roati[2], D. V. Magalhães[1], K. M. F. Magalhães[1], V. S. Bagnato[1]

[1]*Instituto de Física de São Carlos – USP – Brazil*
[2]*LENS and Dipartamento di Fisica, Universit di Firenze, INFN and CNR-INFM, Italy*

Vortices in quantum fluids are a remarkable manifestation of the quantum nature in a macroscopic scale. More than that, vortices are intrinsically related to superfluidity and hence their observation allows a convenient visual signature of such state. Vortices have been produced in many different ways. The most used technique is to use a laser beam focused to the condensate moving faster than the critical velocity [1]. Besides the already existent variety of techniques to generate vortices, new techniques can always provide new and exciting ways to explore this topic. In this work we present a new technique to nucleate vortices in a BEC, where the field generated by a set of two coils is superimposed to the trapping field creating a spherical quadrupole field, which is slightly misaligned with respect to the symmetry axis of a QUIC trap. The current in the coils is periodic in time and this oscillatory excitation couples to the condensate nucleating vortices. As a function of the amplitude of oscillation of the external magnetic field we observe several different behaviors of the condensate cloud. For small amplitudes the condensate oscillate its axis. Increasing the amplitude we observe the formation of one, two, three or more vortices in the cloud as we can see in the figure below. Above a certain amplitude of oscillation we observe uncountable vortices in every direction and this may be an evidence of a turbulent regime in the cloud. The mechanisms involved in the vortices nucleation are not completely understood. Vortices can either be due to the excitation of surface modes of the condensate due to the oscillatory motion of its center-of-mass or due to the phase imprint as described in the theoretical proposal by Mottonen et al[2].

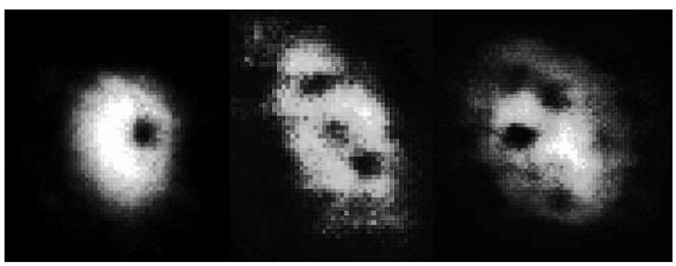


Figure 1: *Images of several vortex configurations in Bose-Einstein condensates observed with our off-axis excitation technique.*

[1]S. Inouye *et al.*, Phys. Rev. Lett. **87**, 080402 (2001)
[2]M. Mottonen *et al.*, Phys. Rev. Lett. **99**, 250406 (2007)

Corrections to Thomas-Fermi approximation for finite temperature condensate:theory and experiment

M. Caracanhas[1], J. A. Seman[1], E. A. L. Henn[1], E. R. F. Ramos[1], E. P. Olimpio[1], G. Roati[2], K. M. F. Magalhães[1], V. S. Bagnato[1]

[1]*Instituto de Física de São Carlos – USP – Brazil*
[2]*LENS and Dipartamento di Fisica, Universit di Firenze, INFN and CNR-INFM, Italy*

The experiments with Bose-Einstein condensates of alkali gases have been successfully described within Thomas-Fermi approximation. At zero temperature there is no thermal cloud and and an explicit analytical relation between the condensed cloud size and parameters of the confining potential shows that[1]. $R^5 N_0^{-1} = cte$, where N_0 is the number of condensate atoms and R is the Thomas-Fermi radius. Increasing number makes the size of the cloud to scale following this relation.
At non-zero temperature, significant interaction between the condensate and the thermal cloud can modify the Thomas-Fermi relation, producing a dimension for the condensate cloud that depends on the condensate fraction. In our experimental setup, this dependence was measured and the result is shown in Fig.1. While large condensate fractions seems to show $R^5 N_0^{-1}$ tending to a constant, small fractions show significant deviation.
To explain our results we construct a Thomas-Fermi model where an explicit interaction between the condensate atoms and the thermal cloud is taken into account. We obtain a semi-classical expression to determine the chemical potential as a function of the temperature, $\mu(T)$, and hence expressing the relation $R^5 N_0^{-1}$ at different temperatures below T_c. The resulting expression is given by

$$R^5 N_0^{-1} = \frac{P_1}{\gamma}\left[1 + P_2(1-\gamma)\right], \qquad (3)$$

where $\gamma = N_0/N$, P_1 is a constant depending on U_0 and ω and P_2 is a universal function. The model is shown as a solid line in Fig.1.
Acknowledgments: Fapesp, CNPq and CAPES.

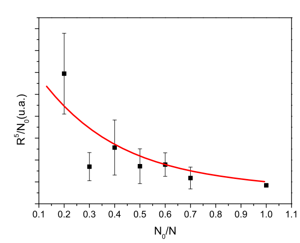


Figure 1: *Dependence of the Thomas-Fermi radius as a function of the condensed fraction showing deviation for smaller fractions of condensed atoms.*

[1]C. J. Pethick and H. Smith, Bose-Einstein Condensation in Dilute Gases, Cambridge University Press (2002)

A Smooth, Inductively Coupled Ring Trap for Atoms

P. F. Griffin, E. Riis, A. S. Arnold

Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK

We propose and numerically investigate a scalable ring trap for cold neutral atoms that surmounts problems of potential roughness and end-effects of trap wires. A stable trapping potential is formed about an electrically isolated, conducting loop in an ac magnetic field by time averaging the superposition of the external and induced magnetic fields. The amenability of micro-fabrication of these ring traps offers the possibility for developing atom interferometry in atom-chip devices.

We consider a single, closed conducting loop of radius $r_{\rm ring}$, formed from a conductor of circular cross-section, radius $r_{\rm wire}$, immersed in a uniform magnetic field, directed perpendicular to the plane of the ring and with an amplitude that varies sinusoidally in time. This driving field and the field due to the induced current in the conductor cancel symmetrically in a ring a small distance inside the metal loop, Fig. 1. The radius of this ring varies in time, but if the magnetic potential varies at a frequency much greater than the atomic motional frequencies then a single trapping radius is found by averaging the field over one cycle [1]. Fig. 2 shows the time-averaged potential for realistic experimental parameters.

In addition to the clear benefit of no end wires the inductively coupled ring trap has the further advantage in that it surmounts the problem of trapping potential roughness caused by the deviation of the current flow from the ideal path through the wire. As was recently demonstrated, these corrugation effects are greatly reduced when ac currents are used [2]. For the configuration considered here this is of relatively minor importance as the distance from the wire to the trapping point is comparatively large, but the general concept of an inductively coupled ring trap scales to much smaller dimensions and is ideally suited for micro-fabrication.

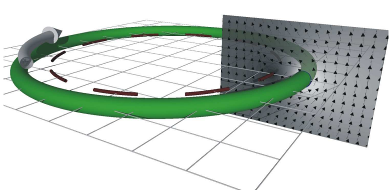


Figure 1: *Schematic of the instantaneous vector fields for the ring trap. The grey–scale in the field slice indicates field magnitude and arrows the field direction.*

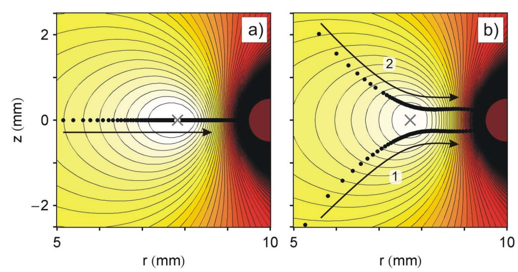


Figure 2: *Magnetic potentials;* ***a)****, no additional fields,* ***b)****, with additional dc quadrupole field. The time–averaged trap minima are marked $\times$, and the instantaneous zeroes of the B–field by $\bullet$.*

[1]P.F. Griffin, E. Riis and A.S. Arnold, Phys. Rev. A **77**, 051402, (2008).
[2]J.-B. Trebbia *et al*., Phys. Rev. Lett. **98**, 263201, (2007).

Formation of vortices in a dense Bose-Einstein condensate

V. P. Barros[1], Ch. Moseley[2], A. Gammal[1], K. Ziegler[2]

[1]*Instituto de Física, Universidade de São Paulo C.P. 66318, 05315-970, São Paulo, Brazil*
[2]*Institut für Physik, Universität Ausgburg, D-86135 Augsburg, Germany*

We consider a rotating dense Bose-Einstein condensate near a Feshbach resonance, where strong interaction effects appear. A relaxation method [1] is employed to study this system beyond Thomas-Fermi approximation. We use a slave-boson model [2] to describe the strongly interacting condensate and derive a generalized non-linear Schrödinger equation with kinetic term for the rotating condensate. In comparison with previous calculations, based on Thomas-Fermi approximation, significant improvements are found in regions, where the condensate in a trap potential is not smooth. The critical angular velocity of the vortex formation is higher than in the Thomas-Fermi prediction.

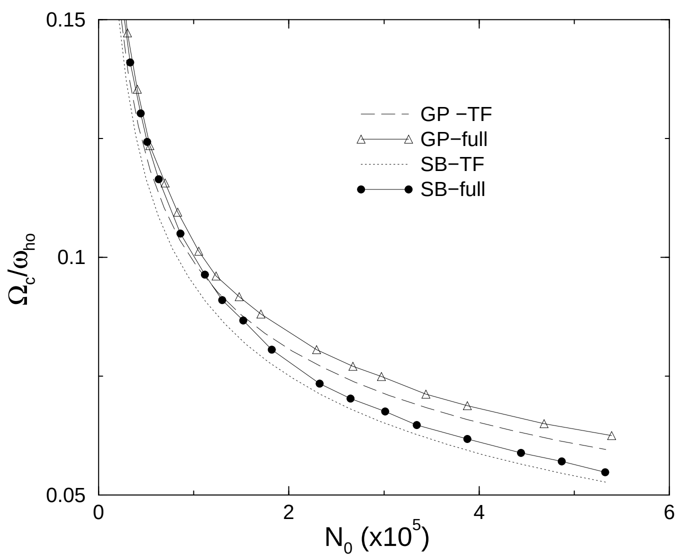


Figure 1: *Critical angular velocity calculated using the Gross-Pitaevskii (GP) equation and and slave-boson (SB) approach. Calculations where performed with Thomas-Fermi(TF) approximation and full calculations with the kinetic term (full).* N_0 *is the number of particles in the condensate. For the SB approach we used* $\beta' = 10$*, that is related to* $\beta = 1/k_B T$ *by scaling parameters.*

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[2]C. Moseley and K. Ziegler, J. Phys. B: At. Mol. Opt. Phys. **40**, 629 (2007).

Experiments on Bose-Einstein Condensate of ^{87}Rb in Finite Temperatures

M. Witkowski[1], R. Abdoul[2], R. Gartman[2], J. Szczepkowski[3], J. Zachorowski[4], M. Zawada[2], W. Gawlik[4]

[1]*Institute of Physics, University of Opole, Opole, Poland*
[2]*Institute of Physics, Nicolaus Copernicus University, Toruń, Poland*
[3]*Institute of Physics, Pomeranian University, Słupsk, Poland*
[4]*Institute of Physics, Jagiellonian University, Kraków, Poland*

We report on our experiments on the dynamics of a mixture of BEC with thermal atoms at temperatures close to critical temperature. We have developed a method of an accurate analysis of absorptive images based on a reliable method of separation of the thermal and BEC contributions. Using this method for analysis of the evolution of the atomic sample released from the magnetic trap, we observe changes of the BEC aspect ratio as a function of the BEC size (atom number) and the ratio between thermal and condensed atom numbers. For pure small condensates we observe departure from the Thomas-Fermi (TF) model but good agreement with the Gross-Pitaevskii (GP) theory (Fig. 1a). However, for mixtures of BEC and thermal atoms, the GP model works well only if the condensate fraction comprises a small number of atoms. For mixtures where the BEC fraction is sufficiently big to justify the TF approximation, we observe departures from the GP picture (Fig.1b). We attribute this departure to extra interactions between the BEC and thermal cloud[1].
This work has been performed in KL FAMO, the National Laboratory of AMO Physics in Toruń and supported by the Polish Ministry of Science.

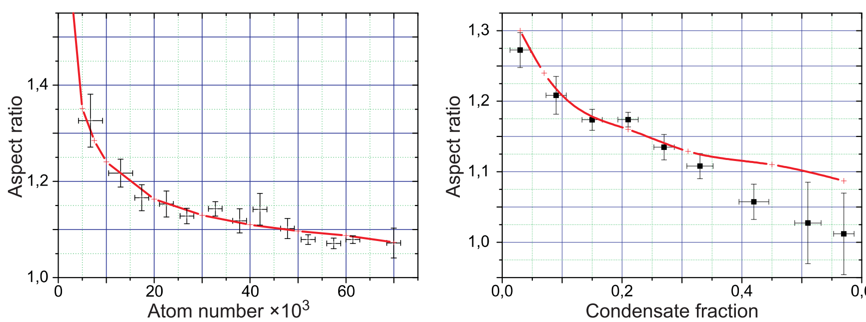

Figure 1: *Aspect ratio of (a) a pure BEC vs. the condensate size (atom number); (b) BEC in a mixture with a thermal cloud vs. the condensate fraction. Solid lines on both plots are predictions of the GP theory.*

[1]F. Gerbier, J. H. Thywissen, S. Richard, M. Hugbart, P. Bouyer, and A. Aspect, "Experimental study of the thermodynamics of an interacting trapped Bose-Einstein condensed gas," *Phys. Rev. A* **70**, 013607 (2004)

Double species Bose-Einstein condensate with tunable interspecies interactions

G. Thalhammer[1], G. Barontini[1], J. Catani[1,2], L. De Sarlo[1], F. Minardi[1,2], M. Inguscio[1,2]

[1]*LENS - European Laboratory for Non-Linear Spectroscopy and Dipartimento di Fisica, Università di Firenze, Sesto Fiorentino (Firenze), Italy*
[2]*CNR-INFM, Sesto Fiorentino (Firenze), Italy*

We characterize two interspecies Feshbach resonances of the Bose-Bose mixture ^{87}Rb–^{41}K, with both species in the lowest Zeeman state[1]. By means of these Feshbach resonances, occurring around 35 G and 79 G, we are able to produce a double species Bose-Einstein condensate with tunable interspecies interactions. We demonstrate that we can achieve the double BEC on both sides of the Feshbach resonance at 79 G, with attractive and repulsive interactions. While a BEC of two different species has been obtained earlier[2,3,4], we provide for the first time a double species BEC with tunable interactions. We also locate the positions of vanishing interspecies scattering length, i.e., the zero-crossings. This is especially relevant to explore the quantum phases of the double-species Bose-Hubbard model[5].

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[3]S. B. Papp, J. M. Pino, and C. E. Wieman, arXiv:cond-mat/0802.2591
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[5]E. Altman, W. Hofstetter, E. Demler, and M. D. Lukin, New J. Phys. 5, 113 (2003)

All-optical production of ^{7}Li Bose-Einstein condensation using Feshbach resonances

N. Gross, L. Khaykovich

Department of Physics, Bar-Ilan University, Ramat-Gan, 52900 Israel

Evaporative cooling of ^{7}Li atoms in a magnetic trap is a challenging task due to several reasons [1]. First, the atoms posses a relatively small scattering length and a high two-body loss rate [2]. Second, the initial phase space density is unfavorably limited by the absence of polarization-gradient cooling mechanism. Third, since the scattering length drops with increased temperature and crosses zero at $T = 8$ mK [3], the use of adiabatic compression to increase the elastic collisional rate is ineffective. In this work we show an all-optical method of making ^{7}Li condensate using the tunability of the scattering length in the proximity of a Feshbach resonance [4]. We report the observation of two new Feshbach resonances on $|F = 1, m_F = 0\rangle$ state. The narrow (broad) resonance of 7 G (34 G) width is detected at 831 ± 4 G (884^{+4}_{-13} G). Position of the scattering length zero crossing between the resonances is found at 836 ± 4 G. The broad resonance is shown to be favorable for run away evaporation which we perform in a crossed-beam optical dipole trap derived from a 100 W Ytterbium fiber laser. Starting directly from a phase space density of a magneto-optical trap we observe a Bose-Einstein condensation threshold in less than 3 s of forced evaporation.

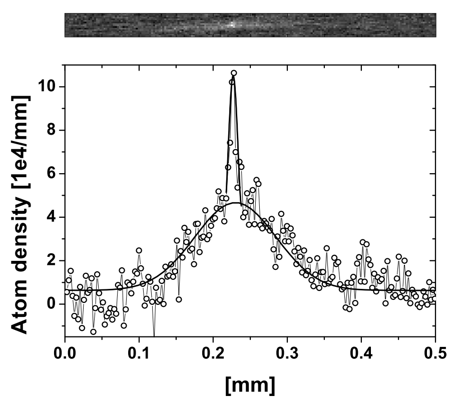

Figure 1: *On-set of BEC. In-situ absorption imaging of atoms at the BEC threshold. The thermal atomic cloud is fitted with a Bose-Einstein distribution function which yields the temperature of* 380 ± 40 *nK. The number of atoms in the BEC is* ~ 700.

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Resolving and Addressing Spin-1 BECs in Individual Sites of a CO_2-laser Optical Lattice

E. Bookjans, C. Hamley, G. Behin-Aein, P. Ahmadi, M. Chapman

Department of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA

We report on the direct production of an array of up to 30 independent ^{87}Rb spin-1 BECs in a large period standing wave potential created by a CO_2 laser. Using a high resolution imaging system, we optically image the individual lattice sites. Additionally, single sites are selectively addressed in a magnetic field gradient using microwave transitions. This system is ideally suited for many applications ranging from quantum information processing, to simulation of solid state systems, and to studies of condensates with small numbers.
We also present high resolution photoassociation spectroscopy of a ^{87}Rb spin-1 BEC to the 1g ($P_{3/2}$) v=152 excited molecular state manifold. We demonstrate the use of spin dependent photoassociation to experimentally identify hyperfine-rotation structure of the molecular state. These identifications are compared to a hyperfine-rotational Hamiltonian for Hund's case (c) which closely accounts for the frequency splitting of all observed hyperfine states. We have also identified the molecular states that are solely created through total spin 0 or 2 scattering channels.

Towards Dual BEC: Zeeman slower approach

M. Gibbs, A. Seltzman, E. Thiemann, T. Ishikawa, G. Telles, C. Raman

School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA

We present the features of an experimental apparatus, specially built to produce and investigate dual species atomic Bose-Einstein condensates of ^{23}Na and ^{87}Rb. The system has many interesting capabilities including a dual oven with a distillation chamber for safe handling, the ability to generate kilogauss magnetic fields, and high optical access. Our approach incorporates a Zeeman slower, capable of delivering a large flux of both Na and Rb atoms to be captured in a dual species magneto-optical trap, see Fig.1 below. Later, ^{87}Rb atoms are sympathetically cooled by large numbers of ^{23}Na atoms, evaporativelly cooled down to the quantum degeneracy. We are interested in observing quantum statistical effects, interaction tuning, and production of heteronuclear ultracold dimer molecules. Future experiments and ideas may be presented.

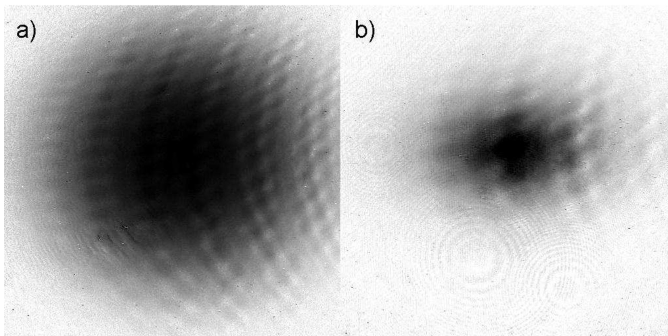

Figure 1: *Absorption images of our overlapped two species magnetic trap (MT) of:a) ^{23}Na; and b) ^{87}Rb. We have been able to load around 10^9 Na atoms and 10^8 ^{87}Rb in our MT.*

Generating Nonclassical States in Atom-Optics via Self Interaction.

S. A. Haine[1,2], M. T. Johnsson[1,2]

[1] *Australian Research Council Centre for Excellence in Quantum Atom Optics*
[2] *University of Queensland, Brisbane, Australia*
[3] *Australian National University, Canberra, Australia*

The creation of the optical laser and the development of quantum optics has allowed tests of many fundamental properties of quantum mechanics[1]. The ability to create quantum squeezing is an important prerequisite for many of these tests as it allows the creation of continuous variable entanglement between the amplitude and phase of two spatially separated optical beams. With the advent of the atom laser, there is much interest in creating a squeezed atomic beam as it allows us to revisit many of these tests using massive particles rather than photons. Atom lasers are also of interest for precision measurement. Interferometry using massive particles promises hugely increased sensitivity over that available optically. As one example, given equal enclosed area and particle flux, the sensitivity of atom interferometer gyroscopes exceeds that of photonic gyroscopes by a factor of 10^{11} [2]. A seemingly obvious route to take advantage of this feature is the use of atom lasers in interferometry. However, the fundamental limit to the sensitivity of any measurement will be the atomic shot noise. The sensitivity can be increased by quantum squeezing. Squeezing is arguably more important in an atom interferometer, as the flux cannot be increased arbitrarily.

We propose a method for generating quantum squeezing in atom-optical systems. We show that it is possible to generate squeezed atom lasers, and Bose-Einstein condensates with squeezed occupation numbers by utilising the nonlinear atomic interactions caused by s-wave scatting. We develop an analytic model of the process which we compare to a detailed multimode stochastic simulation of the system using phase space methods, and show that significant quadrature squeezing can be generated, and that this squeezing is easy to control by adjusting parameters such as the outcoupling rate. Furthermore, we show that by interfering two atom laser beams from the same condensate, we can convert quadrature squeezing into intensity squeezing in one of the beams, or intensity difference squeezing between the two beams, independent of the initial phase statistics of the condensate. Finally we show that significant squeezing can be obtained in an experimentally realistic system and suggest ways of increasing the tunability of the squeezing[3]. We propose a simple method for creating BEC's with squeezed occupation numbers, via a similar method.

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[3] M. T. Johnsson and S. A. Haine, Phys. Rev. Lett. **99**, 010401 (2007).

The cranked-Hartree-Fock-Bogolibov description for Fragmented Bose-Einstein Condensates

N. Hamamoto[1], M. Oi[2,3], N. Onishi[4]

[1]*Integrated Information Processing Center, Niigata University, Japan*
[2]*Department of Physics, University of Surrey, UK*
[3]*Nuclear Theory Division, RIKEN, Japan*
[4]*Department of Information System, Tokyo International University, Japan*

A possibility of a fragmented Bose-Einstein condensate (FBEC) was suggested in 1982 by Nozières and Saint James, for an infinite system. The realization of the BEC in the finite trap stimulated reinvestigations of a possible FBEC in the trap. Recently, Liu et. al. pointed out that a FBEC is realized for a 2-dimensional Bose system in an isotropic harmonic trap, using the exact diagonalization technique[1].

We recently developed a computer code based on the cranked Hartree-Fock-Bogoliubov (CHFB) theory so as to calculate the yrast states of rotating ultra-cold Bose gases [2 3]. In the CHFB theory, the creation and annihilation operators for the ground state ($c_0^\dagger$,c_0) are not set to be $\sqrt{N}$, where N is the number of atoms. Then, the quasi-particle operators $a_i^\dagger, a_i$ are given as $a_i^\dagger = \sum_\alpha U_{\alpha i} c_\alpha^\dagger + V_{\alpha i} c_\alpha$, $a_i = \sum_\alpha U_{\alpha i}^* c_\alpha + V_{\alpha i}^* c_\alpha^\dagger$, where α includes both the ground and excited states. Therefore, the ground state is not expressed as the coherent state, but as the Thoulessian ansatz $\mathcal{N} \exp(f_{\alpha\beta} c_\alpha^\dagger c_\beta^\dagger)$. Different from the Gross-Pitaevski approach, this ansatz wavefunction can represent a fragmented condensate in which macroscopic occupations are made to multiple single-particle states.

Within the framework of the CHFB theory, we developed a method called "Valence Field Expansion", which enables us to calculate matrix elements of an arbitrary 2-body interaction. [3] Using this new technique, we calculate the yrast states of interacting Bose gases in a deformed trap through the δ-type interaction. In this work, we show that the yrast state changes its nature from a fragmented BEC to a single BEC as the trap potential gets deformed. We also discuss conditions for the fragmented and single BEC to be formed in terms of the deformation of the trap and the strength of a 2-body force.

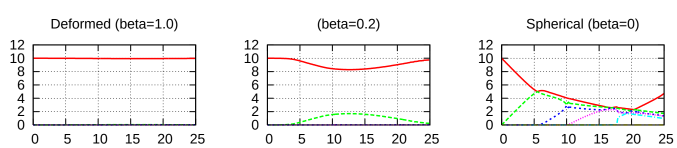

Figure 1: *Eigenvalues of the density matrix as a function of angular momentum for a rotating Bose gas with the total particle number $N = 10$. A FBEC and a single BEC are produced in the spherical (right) and deformed (left) traps, respectively.*

[1]Xia-Ji. Liu et. al. Phys. Rev. Lett. **87** 030404 (2001)

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Quantum Brownian Motion in a Bose-Einstein Condensate

S. E. Hoffmann, P. D. Drummond

ACQAO, School of Physical Sciences, University of Queensland, Brisbane 4072, Australia

Classical Brownian motion is the random walk of a particle, large enough to behave classically, due to collisions with the molecules of the fluid in which it is immersed. The theoretical understanding of this process was one of the efforts that earned a Nobel Prize for Albert Einstein, and involves the fundamental connection between fluctuations and dissipation.

We propose to investigate an analogous system in which quantum mechanics must play a central rôle: A single impurity atom (or a small number) immersed in a Bose-Einstein condensate (BEC) of a different species. We refer to the behaviour of the impurity as quantum Brownian motion.

Experimental realization of such a system may be possible by using optical tweezers to place a small number of rubidium atoms in a sodium BEC, for example.

We apply quantum field-theoretic techniques and phase-space methods to investigate two questions.

- What is the behaviour of an impurity atom when placed into a BEC in a state that is localized on a scale much smaller than the extent of the BEC and that has zero average momentum? The observables we investigate in direct phase-space simulations are the position and momentum densities of the impurity, to see whether the spreading rate of the position wavepacket is influenced by its environment. Self-trapping[1], in which the impurity creates a potential minimum for itself by distorting the BEC, is seen to play an important rôle.
- What is the behaviour of the impurity when introduced with a nonzero average velocity? We have theoretical expectations concerning this problem. In Landau’s picture[2], an impurity moving through a superfluid BEC has no mechanism for energy loss to phonons if the velocity is below the speed of sound for the medium. Recent experiments and theoretical investigations have called into question some of the details of this picture. An experiment[3] on laser stirring of a trapped condensate found a critical velocity for energy dissipation much less than the speed of sound due to the emission of vortices. A recent calculation[4] of the drag force on a moving (classical) obstacle in a BEC found a nonzero drag force down to zero velocity.

We investigate these questions with direct phase-space simulations, providing a completely quantum-mechanical treatment of the BEC and the impurity.

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[3] C. Raman *et al.* Phys. Rev. Lett. **83**, 2502 (1999)
[4] D.C. Roberts, Phys. Rev. A **74**, 013613 (2006)

Guided-wave atom interferometer with mm-scale arm separation

J. H. T. Burke, B. Deissler, K. J. Hughes, C. A. Sackett

Department of Physics, University of Virginia, Charlottesvile, VA 22904, USA

Guided-wave atom interferometers measure interference effects using atoms held in a confining potential. In one common implementation, the confinement is primarily two-dimensional, and the atoms move along the nearly free dimension after being manipulated by an off-resonant standing wave laser beam. In this configuration, residual confinement along the nominally free axis can introduce a phase gradient to the atoms that limits the arm separation of the interferometer. We experimentally investigate this effect in detail, and show that it can be alleviated by having the atoms undergo a more symmetric motion in the guide. This can be achieved by either using additional laser pulses or by allowing the atoms to freely oscillate in the potential. With these techniques, we demonstrate interferometer measurement times up to 72 ms and arm separations up to 0.42 mm with a well controlled phase, or times of 0.91 s and separations of 1.7 mm with an uncontrolled phase.

Three-dimensional character of atom-chip-based rf-dressed potentials

J. J. P. van Es[1], S. Whitlock[1], T. Fernholz[1,2], A. H. van Amerongen[1], N. J. van Druten[1]

[1] *Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands*
[2] *QUANTOP–Danish Quantum Optics Center, Niels Bohr Institute, Copenhagen, Denmark*

We experimentally investigate the properties of radio-frequency-dressed potentials for Bose-Einstein condensates on atom chips. The three-dimensional potential forms a connected pair of parallel waveguides[1]. We show that rf-dressed potentials are robust against the effect of small magnetic-field variations on the trap potential. Long-lived dipole oscillations of condensates induced in the rf-dressed potentials can be tuned to a remarkably low damping rate. We study a beam splitter for Bose-Einstein condensates and show that a propagating condensate can be dynamically split in two vertically separated parts and guided along two paths. The effect of gravity on the potential can be tuned and compensated for using a rf-field gradient.

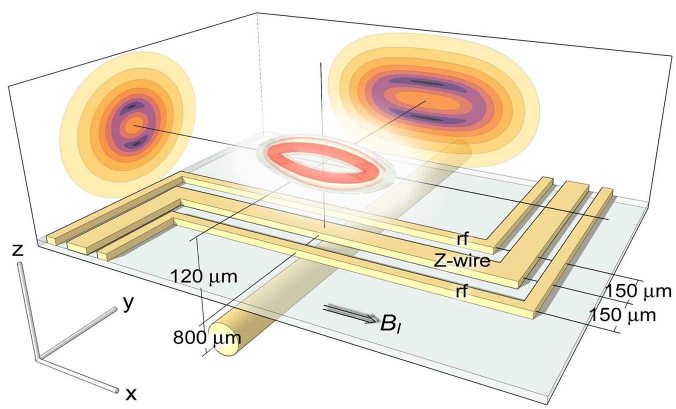

Figure 1: *Schematic of the atom chip and the rf-dressed potentials it produces. The central Z-shaped wire carries a dc current and is used together with an external bias field along y to produce a Ioffe-Pritchard magnetic microtrap. Positioned next to the Z-shaped wire are two wires which carry rf currents. Potential-energy cross-sections for vertical splitting are depicted on the back planes of the image. A sketch of the trapped atom cloud is shown in the center, above the Z-shaped wire.*

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Bragg Spectroscopy of a Strongly Interacting ^{85}Rb Bose-Einstein Condensate

J. M. Pino[1], S. B. Papp[1], R. J. Wild[1], S. Ronen[1], C. E. Wieman[2], D. S. Jin[1], E. A. Cornell[1]

[1] *JILA, Quantum Physics Division, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA*
[2] *University of British Colombia, Vancouver, BC V6T 1Z1, Canada*

We report on measurements of the large-momentum excitation spectrum of a strongly interacting Bose-Einstein condensate (BEC). Using a magnetic-field Feshbach resonance to tune atom-atom interactions in the condensate, we reach a regime where quantum depletion of the ground state and beyond mean-field corrections to the condensate chemical potential are significant. The Bragg resonance line shift due to strong interactions was found to be significantly less than that predicted by a mean-field theory, and demonstrates the onset of beyond mean-field effects in a gaseous BEC.

A High Flux Atom Laser for Interferometry

J. Dugué[1,2], M. Jeppesen[1], C. Figl[1], N. P. Robins[1], J. D. Close[1]

[1]*ACQAO, The Australian National University, Canberra, Australia*
[2]*Laboratoire Kastler-Brossel, ENS, CNRS, UPMC, IFRAF, Paris, France*

The atom laser, first demonstrated at MIT[1], is a promising source for atom interferometry for fundamental and practical applications. Although the quantum statistics and flux, in theory, limit the signal to noise ratio in an interferometric measurement, the classical properties, such as intensity fluctuations, frequency fluctuations and spatial mode profile often prevent an experiment from reaching its fundamental noise floor. Recent experimental studies[2,3] have shown that it is possible to get a clean spatial mode profile using an RF transition provided the outcoupling cut is applied from the bottom of the condensate. The flux of an atom laser is proportional to the outcoupling Rabi frequency and the number density of the atoms in the vicinity of the outcoupling cut. As there is an upper limit on the outcoupling Rabi frequency for classically quiet operation[4], it is desirable to outcouple from the centre of the condensate, where the number density and therefore the atom laser flux, is maximized. We show that for a Raman atom laser, in contrast to an RF atom laser, we can outcouple from the centre of the condensate and still retain a clean spatial mode[5].
In our experiment we create ^{87}Rb condensates of 5×10^5 atoms in the $F = 1, m_F = -1$ trapped state that we couple to the $F = 1, m_F = 0$ un-trapped state via an optical Raman transition[6]. The atoms then receive a momentum kick from the absorption and emission of photons. As a result, they leave the condensate quickly so that adverse effects due to the mean-field repulsion are reduced. As the kick increases, the divergence is reduced and the beam profile improved. The beam quality parameter[2] is also measured and the experimental results are compared to theoretical models finding excellent agreement.
We also report[7] on the experimental realization of a multibeam atom laser. A single continuous Raman atom laser is outcoupled from a condensate before being subsequently split into up to five atomic beams with slightly different momenta. The splitting process itself is a realization of Bragg diffraction driven by each of the optical Raman laser beams independently, which is a significantly simpler implementation of an atomic beam splitter. The multiple, nearly copropagating, coherent atomic beams resulting from this process could be of use in interferometric experiments.

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Cleaning of magnetic substates in an optical dipole trap

C. Käfer[1], R. Bourouis[2,1], J. Eurisch[1], T. Boll[1], H. Helm[1]

[1]*Department of Molecular and Optical Physics, Freiburg, Germany*
[2]*Institute for Applied Physics, Bonn, Germany*

We use an optical dipole trap, realized by the tight focus of a 25 Watt CO_2 laser, to cool ^{87}Rb atoms by lowering the dipole trap depth (forced evaporation) to temperatures below 100 nK. We end up with a sample of $2-5\times10^4$ degenerate atoms. By applying an asymmetric and inhomogeneous magnetic field at the end of the forced evaporation phase, prior to switching off the CO_2-laser, we are able to remove atoms in the magnetic levels $m_f \neq 0$ from the trap. The magnetic field is realized by operating anti-Helmholtz coils with unbalanced currents. We monitor this process by photographing the time-dependent emission of atoms, and by probing the residual atoms in the trap by a Stern-Gerlach experiment. We show that a complete removal of atoms in the states $m_f \neq 0$ is possible by appropriate adjustment of the magnetic field distribution. The experimental observations are supported by numerical simulations of atom trajectories in our experiment.
Our cigar shaped dipole trap has an axial Rayleigh length of ≈ 400 μm and a radial waist radius of ≈ 35 μm. The trapping force along the axial direction is the weakest and therefore the application of an inhomogeneous field provides exit ports for atoms along the axial direction when the magnetic field Zero does not coincide with the center of the dipole trap. To do our experiments, we first transfer all m_f states from a MOT into the optical dipole trap by polarization-gradient cooling. After turning off the MOT and the magnetic field we begin a phase of forced evaporative cooling over a five seconds long ramp. At the end of the ramp the dipole trap laser operates near 200 mW and is kept constant over the final 100 ms before turning off the CO_2 laser. During this period the additional magnetic force is turned on and the free fall sequence (in the presence of the magnetic field), is photographed by absorption imaging. A splitting into three clouds along the vertical direction is observed when the magnetic field is turned on when the CO_2 laser is turned off. However, by applying the magnetic field earlier the emission of atoms along the axial direction (already in the evaporation phase) is observed and shown to derive from atoms in the magnetic substates $m_f = \pm 1$ being emitted from the shallow dipole trap, as shown below.

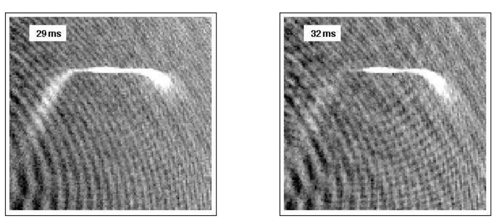

Figure 1: *Absorption pictures for two different switching times* $\Delta t = \{29,\, 32\}$ *ms at a fixed free fall time* t_{fall} *= 1 ms.*

First Determination of the Helium $2\,^3P_1 - 1\,^1S_0$ Transition Rate

R. G. Dall, K. G. H. Baldwin, L. J. Byron, A. G. Truscott

ARC Centre of Excellence for Quantum-Atom Optics. Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia.

Quantum electrodynamics (QED) is one of the most rigorously tested fundamental theories of modern physics, for which the atomic energy levels of helium and heliumlike ions represent an important test bed. Helium is the simplest multielectron atom, enabling theoretical calculations to be performed with greater accuracy than for more complex species. By contrast, other atomic parameters such as transition rates are much harder to determine, both experimentally and theoretically, with accuracies often at the percent level. The behavior of the transition rates of heliumlike atoms in an isoelectronic sequence is a case in point that has received considerable theoretical attention[1,2,3]. A number of experimental determinations of the transition rates of highly ionized heliumlike species have tested these QED predictions, but there have been no published measurements of the decay of helium atoms from the $2\,^3P$ states to the ground state.

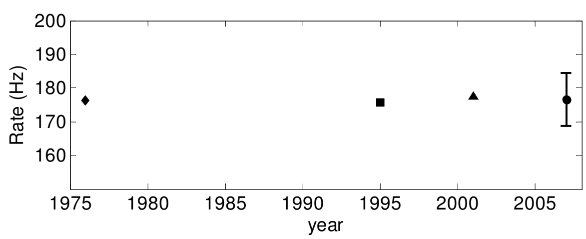

Figure 1: *(a) Historical progress of theoretical determinations for the helium $2\,^3P_1 - 1\,^1S_0$ decay rate (references shown), together with the experimental value (and uncertainty) from the present work. References 1-4, left to right.*

We present the first experimental determination of the $2\,^3P_1 - 1\,^1S_0$ transition rate in helium [4] and compare this measurement with theoretical quantum-electrodynamic predictions. The experiment exploits the very long ($\sim$1 minute) confinement times obtained for atoms magneto-optically trapped in an apparatus used to create a Bose-Einstein condensate of metastable ($2\,^3S_1$) helium. The $2\,^3P_1 - 1\,^1S_0$ transition rate is measured directly from the decay rate of the cold atomic cloud following 1083 nm laser excitation from the $2\,^3S_1$ to the $2\,^3P_1$ state, and from accurate knowledge of the $2\,^3P_1$ population. The value obtained is 177 ± 8 s^{-1}, which agrees very well with theoretical predictions, and has an accuracy that compares favorably with measurements for the same transition in heliumlike ions higher in the isoelectronic sequence.

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[2] W. R. Johnson, D. R. Plante, and J. Sapirstein, Adv. At. Mol. Opt. Phys. **35**, 255 (1995).
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Single mode guiding of an atom laser beam

S. Hodgman, R. G. Dall, M. T. Johnsson, K. G. H. Baldwin, A. G. Truscott

ARC Centre of Excellence for Quantum-Atom Optics. Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia.

Atoms coherently output-coupled from a Bose-Einstein condensate (BEC) form a coherent beam of matter waves, or 'Atom laser'. Like its optical counterpart, the atom laser has the potential to revolutionise future atom interferometric sensors, in which a high flux of collimated atoms is required. Most condensates are confined in a magnetic potential, where to achieve maximum flux the atom laser beam is outcoupled from the centre of the BEC. This leads to atoms in the atom laser beam probing the high density region of the BEC via s-wave interactions and experiencing a large repulsive force (so-called 'mean field' repulsion). These interactions strongly distort the atom laser beam, resulting in a far from ideal spatial profile that exhibits a double peaked structure (see Fig 1(c)) [1,2]. A method to alleviate this problem is to use an optically trapped BEC. In such case an atom laser is produced by simply turning down the optical power of the trap and letting atoms fall out of the spatial minimum of the trap where the atomic density is low. Furthermore, by not extinguishing the optical trap completely the atom laser beam experiences a weak confining potential that acts like an optical fibre to guide the atoms.

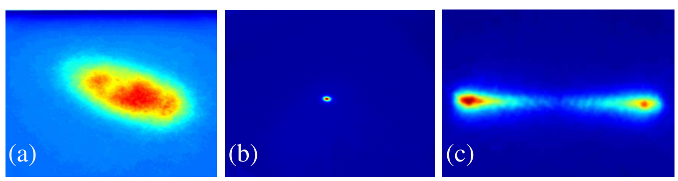

Figure 1: *(a) Spatial profile of the optically trapped BEC if no guide is implemented, (b) single mode guided profile and (c) usual He* atom laser profile. Each image is 1.1 cm by 0.8 cm.*

Here we demonstrate single mode guiding of a metastable helium (He*) atom laser using a far detuning laser beam. Atoms cooled to $\sim 1\ \mu$K in a magnetic trap are transferred to an optical trap aligned in the vertical direction, where BEC is achieved. Subsequent lowering of the optical potential by a factor of ~ 100 in 10 ms releases the atoms into the guide and they fall under gravity for 200 mm where they strike a multi-channel plate (MCP) and are imaged. The whole process is adiabatic allowing the atoms in the BEC to transfer smoothly from the ground state of the trap to the groundstate of the guide. The resulting guided profile can be compared with the more usual atom laser profile as well as the spatial profile of the optically trapped BEC if no guide is implemented (see Fig. 1).

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Dynamics of a BEC in a 3D double-well potential

K. Maussang[1], G. E. Marti[1,2], T. Schneider[1,3], R. Long[1], J. Reichel[1]

[1] *Laboratoire Kastler-Brossel, ENS, CNRS, 24 rue Lhomond, 75005 Paris, France*
[2] *University of California, Berkeley, California 94720 Berkeley, USA*
[3] *Present address: Institut für Experimentalphysik,Heinrich Heine Universität, 40225 Düsseldorf, Germany*

A Bose-Einstein condensate in a double-well provides an elegant combination of a simple system, analytically solvable and applicable to interferometry, while still featuring rich dynamics. The competition between tunneling and on-site interactions is well described by a nonlinear Hamiltonian, similar to the Kerr Hamiltonian in optics or the Bose-Hubbard Hamiltonian in condensed matter physics, which allows for the deterministic preparation of spin squeezed and other nonclassical quantum states.

Spin squeezed states in particular have attracted much attention because they are robust, comparatively easy to produce, and permit measurements of atomic clocks and interferometers below the standard quantum limit. They can be created as number-squeezed states during the splitting of a single BEC in a double-well, a process studied both theoretically[1] and experimentally[2]. So far only indirect evidence of squeezing in a double-well has been demonstrated[2]. We directly measure the atom number statistics of a BEC in double-well and its dependence on the splitting dynamics, atom loss and atom number.

We implement a double-well on an atom chip that combines compactness, fast cycle times, and flexible trap geometries. While we currently use only one double-well, our two-layer chip design creates smooth static magnetic multi-well 3D potentials in linear and topologically connected geometries. Our chip and imaging system are compatible with small and micro BECs ranging from tens to thousands of ^{87}Rb atoms.

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First realization of Bose-Einstein condensation in microgravity

T. Könemann[1], W. Brinkmann[1], H. Müntinga[1], C. Lämmerzahl[1], H. Dittus[1], T. van Zoest[2], W. Herr[2], S. Seidel[2], N. Gaaloul[2], Y. P. Singh[2], E. M. Rasel[2], W. Ertmer[2], W. Lewoczko-Adamczyk[3], M. Schiemangk[3], A. Peters[3], A. Vogel[4], K. Bongs[4], K. Sengstock[4], T. Steinmetz[5], J. Reichel[5], T. W. Hänsch[5], E. Kajari[6], R. Walser[6], W. P. Schleich[6]

[1]*ZARM, University of Bremen, Germany*
[2]*Institute of Quantum Optics, Leibniz University of Hanover, Germany*
[3]*Institute of Physics, Humboldt-University of Berlin, Germany*
[4]*Institute of Laser-Physics, University of Hamburg, Germany*
[5]*Max-Planck-Institute of Quantum Optics, Munich, Germany*
[6]*Institute of Quantum Physics, University of Ulm, Germany*

Since the possibility of trapping and cooling neutral atoms, ultracold quantum degenerate gases have shifted boundaries in a growing field of modern physics. The current developments in the domain of atom optics lead to an utilization of ultracold quantum matter techniques in unique practical applications as high-precision atomic clocks, atom interferometer technologies and inertial sensing instruments for gravity field mapping, underground structure detection, autonomous navigation, as well as precision measurements in fundamental physics. The expectations of even higher precision measurements can be performed by arbitrarily extending the time of unperturbed evolution of quantum degenerate systems. In respect thereof weightlessness provides an outstanding basis for such applications and measurements.

We report on the first experimental demonstration of rubidium Bose-Einstein condensates in the environment of weightlessness at the earth-bound short-term microgravity laboratory Drop Tower Bremen, a facility of ZARM ("Center of Applied Space Technology and Microgravity") - University of Bremen. This pilot project is performed within the QUANTUS ("Quantum Systems in Weightlessness") collaboration[1,2] to study the possibilities of Bose-Einstein condensation experiments in free fall on earth and the feasibility of ultracold quantum matter techniques on space-based platforms. Our approach is based on a compact, mobile, robust and autonomous operating drop capsule experiment to currently realize weightless Bose-Einstein condensates with longest time of flights (up to 1 second) and adiabatic expansions to very shallow traps (lower than 20 Hz). For this purpose the drop capsule setup has to withstand decelerations of around 50g on every free fall. So far, we have successfully accomplished more than 150 drops with the QUANTUS apparatus since the beginning of November 2007.

The pilot project QUANTUS gratefully acknowledges the support from the DLR ("German Aerospace Center").

[1]A. Vogel et al., Appl. Phys. B 84, no. 4, 663-671 (2006)
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Universality of Bose-Einstein condensation of weakly interacting multi-component atomic gas close to high symmetry point

T. Blanchard[1,2], A. B. Kuklov[1], B. V. Svistunov[3,4]

[1]*Department of Engineering & Physics, CSI,CUNY, Staten Island, 10314, USA*
[2]*Ecole normale supérieure de Cachan 61, 94235 Cachan, France*
[3]*Department of Physics, University of Massachusetts, Amherst, MA 01003, USA*
[4]*Russian Research Center Kurchatov Institute, 123182 Moscow, Russia*

We examine a possibility that BEC of N-component weakly interacting Bose gas with the symmetry group $\mathrm{O}(2N)$ broken down to a subgroup is preempted by spontaneous breaking of this subgroup. This implies condensation of a quadratic form $M_{ab} = \langle \Psi_a^* \Psi_b \rangle$ (or $M_{ab} = \langle \Psi_a \Psi_b \rangle$) before atomic (bosonic) fields $\psi_a = \langle \Psi_a \rangle, a = 1, 2, ..., N$ become condensed. As an example, phase separation could take place before BEC in a spinor $S = 1/2$ two-component gas.

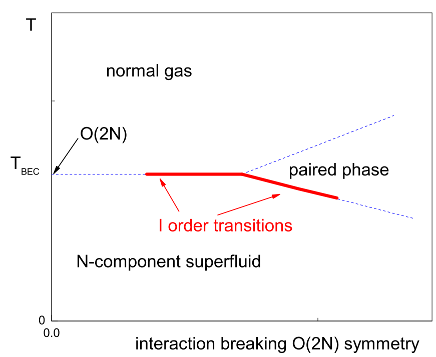

Figure 1: *Generic phase diagram of weakly interacting BEC*

Generic phase diagram,Fig.1,is obtained by introducing Landau free energy functional $H(M_{ab}, \psi_a)$. In particular, there is a term $\sim M_{ab} \psi_b^* \psi_a + c.c.$ (or $\sim M_{ab} \psi_b^* \psi_a^* + c.c.$)[1]. It is important that for small symmetry breaking interactions, the transition is *always of II order* in the universality class dictated by the structure and symmetry of the order parameter and Hamiltonian. Another important aspect is that the intermediate phase (we call is *paired*) may not be present in a particular model because specific microscopic parameters just don't map onto the corresponding region of the Landau functional. As a specific example, we have performed Monte Carlo simulations of spinor $S = 1/2$ Bose gas with the tendency to phase separation and has shown that its phase diagram, while featuring II and I order lines of BEC transitions, does not contain *paired* phase.

[1]A.B. Kuklov, N.V. Prokof ev, B.V. Svistunov, PRL **92**,050402-1(2004)

Towards thermal melting of a vortex lattice in a rotating 2D BEC

G. Lamporesi, S. Tung, V. Schweikhard, E. A. Cornell

JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA

Compared to 3D systems, superfluids in a 2D geometry are characterized by much larger phase fluctuations. At very low temperatures rotating superfluids in 2D present a regular vortex crystal. As the temperature of the system increases, the vortex crystal undergoes a structural phase transition and melts into a liquid phase.

We are experimentally investigating the transition between the vortex crystal phase and the vortex liquid phase in a rotating 2D BEC as the temperature of the system changes.

A blue-detuned 1D vertical optical lattice (see Figure 1) is used to slice a 3D condensate into many layers and by increasing the lattice depth one can achieve the quasi-2D regime for individual layers. The superfluid can be kept under rotation in a controlled way using a weak rotating 2D optical lattice as a stirring potential. A slice imaging technique is employed in order to selectively image a single 2D layer from the top and be able to directly observe its vortex pattern.

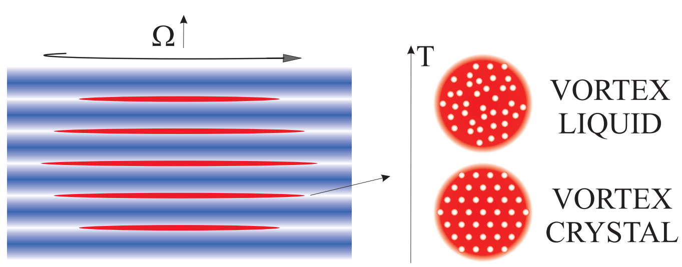

Figure 1: *Rotating BEC in a blue-detuned 1D vertical optical lattice (**left**). Each single rotating pancake is expected to present a vortex pattern (**right**) that will be more (crystal phase) or less (liquid phase) regular, depending on the temperature of the whole system.*

Creating a supersolid in one-dimensional Bose mixtures

L. Mathey[1], Ippei Danshita[2], Charles W. Clark[1]

[1]*Joint Quantum Institute, National Institute of Standards and Technology, Gaithersburg, MD 20899*
[2]*Department of Physics, Faculty of Science, Tokyo University of Science, Shinjuku-ku, Tokyo 162-8601, Japan*

We identify a one-dimensional supersolid phase in a binary mixture of near-hardcore bosons with weak, local interspecies repulsion. We find realistic conditions under which such a phase, defined here as the coexistence of quasi-superfluidity and quasi-charge density wave order, can be produced and observed in finite ultra-cold atom systems in a harmonic trap. Our analysis is based on Luttinger liquid theory supported with numerical calculations using the time-evolving block decimation method. Clear experimental signatures of these two orders can be found, respectively, in time-of-flight interference patterns, and the structure factor $S(k)$ derived from density correlations.

Toward sub-shot-noise fluctuations in coherently split quantum degenerate gases

J. McKeever[1], M. H. T. Extavour[1], L. J. LeBlanc[1], A. B. Bardon[1], D. M. Jervis[1], T. Schumm[1,2], J. H. Thywissen[1]

[1] *IOS, CQIQC and Dept. of Physics, University of Toronto, Canada*
[2] *Atominstitut der Österreichischen Universitäten, TU Wien, A1020 Vienna, Austria*

We have performed direct measurements of atom number at two output ports of a coherent beam-splitter for a Bose-Einstein condensate (BEC), observing atom-number fluctuations at the shot-noise level. Starting from a BEC in a chip-based magnetic trap, the splitting is achieved by adiabatic transformation from a single-well to a double-well using an oscillating (rf) field[1]. We perform direct detection of atom number at each output port via optical absorption imaging, as shown in Fig. 1.
The double-well BEC system is analogous to a bosonic Josephson junction[2], providing a link with condensed matter physics. One potential application is atom interferometry in confined geometries, of great interest for precision measurements such as sensing local fields and their gradients (gravitational or electromagnetic). Our goal is to observe sub-shot-noise fluctuations[3] directly in the number difference between the two output wells, and study their dependence on splitting dynamics, and trap geometry. We present our progress to date, including characterization of the double-well potentials, evaluation of detection sensitivity, rf field amplitude calibration, and a recent redesign and replacement of our atom chip. We also discuss prospects for a complementary measurement with degenerate fermions.

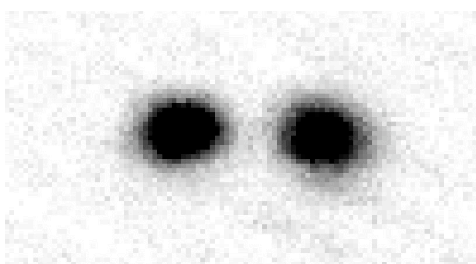

Figure 1: *Absorption image of a coherently split BEC. Separation of the clouds is about* $100\ \mu\mathrm{m}$*, and the total atom number in both clouds is* $N \approx 8 \times 10^3$*. Our detection sensitivity is at the level of* 40 *atoms, limited by optical shot noise.*

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Condition for Dynamical Instability of a Trapped Bose–Einstein Condensate with a Highly Quantized Vortex

M. Mine[1], E. Fukuyama[1], T. Sunaga[1], M. Okumura[2,3], Y. Yamanaka[4]

[1]*Department of Physics, Waseda University, Tokyo 169-8555, Japan*
[2]*CCSE, Japan Atomic Energy Agency, 6-9-3 Higashi-Ueno, Taito-ku, Tokyo 110-0015, Japan*
[3]*CREST (JST), 4–1–8 Honcho, Kawaguchi, Saitama 332–0012, Japan*
[4]*Department of Electronic and Photonic Systems, Waseda University, Tokyo 169-8555, Japan*

We consider a trapped Bose-Einstein condensate (BEC) with a highly quantized vortex. For the BEC with a doubly, triply, or quadruply quantized vortex, the numerical calculations have shown that the Bogoliubov-de Gennes equations, which describe the fluctuation of the condensate, have complex eigenvalues [1]. The presence of the complex eigenvalues is interpreted as a sign of the dynamical instability. This instability is associated with the decay of the initial configuration of the condensate and can occur even at zero temperature, contrary to the Landau instability. In this study, we show an analytic expression of the condition for the existence of complex modes, using the method developed by Rossignoli and Kowalski[2] for the small coupling constant. To derive it, we make the two-mode approximation. With the derived analytic formula, we can identify the quantum numbers of the complex modes for each winding number of the vortex[3]. Our result is consistent with those obtained by the numerical calculation in the case that the winding number is two, three, or four. Furthermore, the three-mode analysis is also performed, and it is confirmed that the condition for the existence of complex modes is not modified. Our conclusion is that the complex modes always exist when the condensate has a highly quantized vortex[3].

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Controlled deflection of cold atomic clouds and of Bose-Einstein condensates

N. Gaaloul[1,2], A. Jaouadi[1,2], L. Pruvost[3], M. Telmini[2], E. Charron[1]

[1]*Laboratoire de Photophysique moléculaire du CNRS, Université Paris-Sud, Bâtiment 210, 91405 Orsay Cedex, France*
[2]*Laboratoire de Spectroscopie Atomique, Moléculaire et Applications, Département de Physique, Faculté des Sciences de Tunis, Université de Tunis El Manar, 2092 Tunis, Tunisia*
[3]*Laboratoire Aimé Cotton du CNRS, Université Paris-Sud, Bâtiment 505, 91405 Orsay Cedex, France*

We present a detailed, realistic proposal and analysis of the implementation of a cold atom deflector using time-dependent far off-resonance optical guides. An analytical model and numerical simulations are used to illustrate its characteristics when applied to both non-degenerate atomic ensembles and to Bose-Einstein condensates. Following a previous study of a cold atom beam splitter[1], we show that it is possible to deflect almost entirely an ensemble of ^{87}Rb atoms falling in the gravity field using for all relevant parameters values that are achieved with present technology[2]. We discuss the limits of the proposed setup, and illustrate its robustness against non-adiabatic transitions.

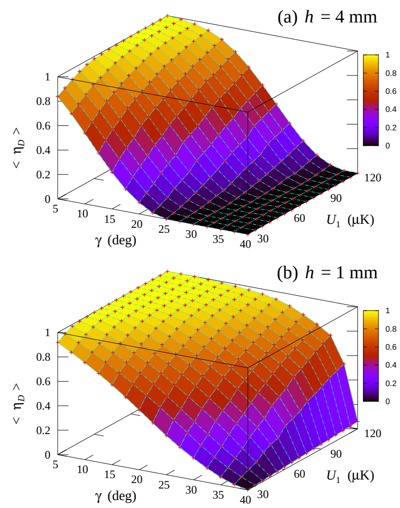

Figure 1: *Total deflection probability $<\eta_D>$ of an atomic cloud of ^{87}Rb of size $\sigma_0 = 0.155$mm at tempurature $T = 10\mu$K, as a function of the deflection angle γ and the depth of the oblique guide potential U_1 .*

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Equilibrium phases of a dipolar spinor Bose gas

M. Vengalattore[1], J. Guzman[1], S. Leslie[1], F. Serwane[1], D. M. Stamper-Kurn[1]

[1] *University of California, Berkeley, USA*

A wide range of correlated materials exhibit spatially inhomogenous phases due to the influence of competing interactions. For instance, in classically ordered systems such as magnetic thin films, the short-range ferromagnetic interaction is frustrated by the spatially anisotropic, long-ranged dipolar interaction. This results in spatially modulated phases exhibiting a wide range of morphologies. Despite the ubiquity of materials that exhibit competing interactions, there remain a range of open questions regarding the properties of such frustrated magnetic systems. Of particular interest in this regard are quantum fluids in which frustrated magnetic order is juxtaposed with superfluidity.

Here, we investigate the properties of quasi two-dimensional $F = 1$ spinor Bose gases of ^{87}Rb under the competing influences of a long-range dipolar interaction and a short-range ferromagnetic interaction. Due to this competition, we observe the spontaneous formation of modulated spin domains that exhibit crystalline order. This self-organized phase is seen both as resulting from a dynamical instability in a transversely magnetized condensate as well as in equilibrium resulting from a gradual cooling of thermal spinor gases. The fact that this crystalline structure is observed under a wide range of initial conditions indicates that this ordered phase could represent an equilibrium configuration of this dipolar quantum fluid.

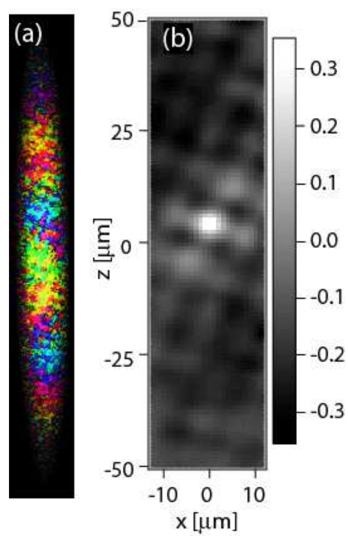

Figure 1: *(a) Spin textures in a spontaneously modulation spinor condensate. The amplitude (orientation) of magnetization is represented by the brightness (hue). (b) The spin correlation function of the dipolar spinor condensate indicates spin domain structures that exhibit crysalline order with a modulation period of around 10 μm.*

Fractional Quantum Hall Physics with Rotating Few-Body Bose Clusters

N. Gemelke[1,2], E. Sarajlic[2], S. Chu[1,3]

[1]*Department of Physics, Stanford University, Stanford, CA 94305, USA*
[2]*Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[3]*Lawrence Berkeley National Laboratory, Berkeley, CA , USA*

A hallmark behavior of low-dimensional, interacting and quantum-degenerate gases is their potential to be mapped onto systems of particles with a statistical character which differs from the constituent particles. In one dimension, this takes the form of the recently observed Tonks-Girardaeu gas[1], where bosons effectively behave as a fermionic gas. In two dimensions the behavior is richer, including the possibility to observe fractional statistics, as occurs in the fractional quantum Hall effect for a two-dimensional electron gas in strong magnetic field. An analogous situation can occur for a rotating and harmonically trapped interacting Bose gas[2] when the total angular momentum of the gas approaches the square of the number of constituent particles. Previous experiments with large rotating superfluid gases[3] have obtained and studied the classical dynamics of large numbers of superfluid vortices, but fall short of the fractional quantum Hall limit. Here we report experiments which attempt to circumvent the technical difficulty of these experiments by working with small numbers of atoms, and attempt to probe the strong particle correlations expected in the fractional quantum Hall regime. We investigate quantum-degenerate few-body clusters of ^{87}Rb atoms confined to an optical lattice potential with locally rotating on-site potentials and repulsive interactions. In the centrifugal limit, when the microtrap rotation frequency differs from its vibration frequency by an amount comparable to the interaction energy, a large scale degeneracy is expected to be broken by particle interactions, and strong atomic correlation is expected in the few-particle ground states. We have designed and implemented an adiabatic pathway for populating these correlated ground states by controlling the rate and amplitude of a rotating deformation to the on-site potential of an optical lattice, similar to the mathod proposed by Popp et al.[4]. We probe short range correlations and momentum distributions by a combination of photoassociation loss and time-of-flight imaging, and compare to expectations from exact numeric evolution of the few-body system with no free parameters. We investigate the role of anharmonic terms in the local trap potential, and their effect on adiabatic pathways to FQH ground states.

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A pumped atom laser

D. Döring, N. P. Robins, C. Figl, M. Jeppesen, G. R. Dennis, J. D. Close

ARC Centre for Quantum-Atom Optics, Physics Department,
Australian National University, Australia

Although the peak flux in atom lasers realised to date is competitive with thermal beams, the duty cycle is low, giving a lower average flux[1 2 3]. We aim to produce a continuous atom laser with a squeezed output for fundamental studies and applications. In this poster, we present the realisation of a pumped atom laser. In our experiment, atoms are transferred by an irreversible Bose enhanced process from a source condensate to the target condensate that is the lasing mode. While the lasing mode is being pumped by the source, atoms are also output-coupled to form a freely propagating atom laser beam. This process runs continuously for 200ms. We test our results against a rate equation model[4]. This is a necessary step towards the production of a truly continuous atom laser. There appear to be two pumping mechanisms that we can access in the experiment. One is related to Raman super-radiance[5 6]. The other is related to a STIRAP process. In order to elucidate the pumping mechanism we have also performed experiments in a short (100μs) pulsed regime. We have investigated both on and off resonant pumping of the lasing mode in this short pulse system.
In future work, we will combine this experiment with an atom delivery system to replenish the source.

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Tailoring Motional States of Strongly Interacting 2D Bose-Einstein Condensates: Creation of Vortices and Antivortices

O. Kärki, K.-A. Suominen

University of Turku, Turku, Finland

We have previously proposed a tailoring method which enables us to move the populations of motional quantum states to another in an efficient way[1]. It is based on time-dependent double-well potentials and one-component description. It can be generalized, so that it can be successfully applied to strongly interacting 1D Bose-Einstein condensates. However, in the case of strongly interacting Bose-Einstein condensates there is a significant difference between 1D and 2D systems.

At the moment, we are studying various 2D variations of the previous method and the consequences of dimensionality. As an example, we have studied a ring shaped geometry, which consists of two harmonic ring traps. That is, we have two harmonic traps, which depend only on radial co-ordinate, within each other. The cross-section of this system reveals the double-well structure. As a result of the tailoring process, we seem to get similar results for a moment compared to 1D system. However, these states are not stable. The situation is similar compared to 2D solitons decaying into vortices and antivortices. This phenomenon is often called snake-instability.

The second geometry we are considering consists of two cylindrically symmetric harmonic traps. The line connecting the bottoms of the wells can be considered as a special direction. The cross-section in that direction shows the double-well structure. However, unlike in the ring trap case, here we have a preferred direction. One, can ask whether it is possible to gain angular momentum during the tailoring process. By changing the preferred direction during the process one might be able to do that.

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A dual-species BEC with tunable interactions

S. B. Papp[1,2], J. M. Pino[1], C. E. Wieman[3,1]

[1]*JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA*
[2]*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, CA 91125, USA*
[3]*University of British Columbia, Vancouver, BC V6T 1Z1, CANADA*

Dual-species quantum gases are currently a subject of significant interest for realizing dipolar interactions between ultracold molecules and probing Efimov quantum states. Understanding how the spatial overlap of the two species changes with interatomic interactions will be important for future experiments.[1] We will report on the observation of controllable phase separation in a dual-species Bose-Einstein condensate with ^{85}Rb and ^{87}Rb.[2] Interatomic interactions of the different components determine the miscibility of the two quantum fluids. In our experiments, we can clearly observe immiscible behavior via a dramatic spatial separation of the two species (Fig. 1). Furthermore a magnetic-field Feshbach resonance is used to change them between miscible and immiscible by tuning the ^{85}Rb scattering length. The spatial density pattern of the immiscible quantum fluids exhibits complex alternating-domain structures that are uncharacteristic of its stationary ground state.

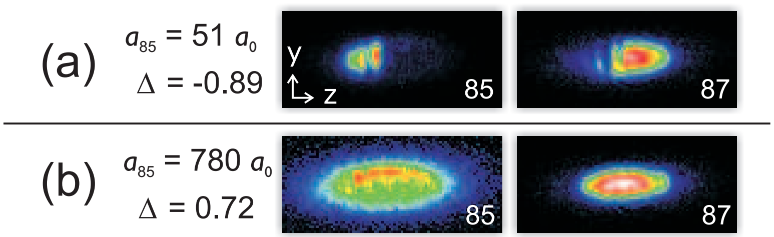

Figure 1: *Absorption images of (a) a phase separated and (b) a miscible mixture of ^{85}Rb and ^{87}Rb. The long direction of all the images represents the position space distribution. The parameter $\Delta = \frac{a_{85}\, a_{87}}{a^2_{85-87}} - 1$ characterizes the tendency of the two clouds to phase separate; the clouds are expected to be immiscible with $\Delta < 0$. The optical depth of the lower ^{85}Rb image has been scaled by a factor of five for clarity.*

[1]S. B. Papp and C. E. Wieman, "Observation of heteronuclear Feshbach molecules from a ^{85}Rb^{87}Rb gas", Phys. Rev. Lett. 97, 180404 (2006).

[2]S. B. Papp, J. M. Pino, and C. E. Wieman, "Studying a dual-species BEC with tunable interactions", arXiv:0802.2591 (2008).

Mind the gap in Raman scattering of a Bose gas !

Patrick Navez[1,2]

[1] *Theoretische Fysica, Katholieke Universiteit Leuven, Belgium*
[2] *Universitaet Duisburg-Essen, Duisburg, Germany*

We explore the finite temperature many body physics through the Raman transition between two hyperfine levels of a Bose condensed atom gas. Unlike the Bragg scattering where the phonon-like nature of the collective excitations has been observed[1], a different branch of thermal atom excitation is found theoretically in the Raman scattering[2] . This excitation is predicted in the generalized random phase approximation and has the parabolic dispersion relation $\epsilon_{1,\mathbf{k}} = \epsilon_g + \mathbf{k}^2/2m$. The gap $\epsilon_g = gn$ results from the exchange interaction energy with the other atoms. During the Raman transition, the transferred atoms become distinguishable from the others and release this gap energy. The scattering rate is determined as a function of the transition frequency ω and the transferred momentum $\mathbf{q}$ and show the corresponding resonance around this gap (see Fig. 1).
Nevertheless, the Raman scattering process is attenuated by the superfluid part of the gas. The macroscopic wave function of the condensate deforms its shape in order to screen locally the external potential displayed by the Raman light beams. This screening is total for a condensed atom transition in order to prevent the condensate to scatter incoherently[2]. The experimental observation of this result would explain some of the reasons for which a superfluid condensate moves coherently without any friction with its surrounding.

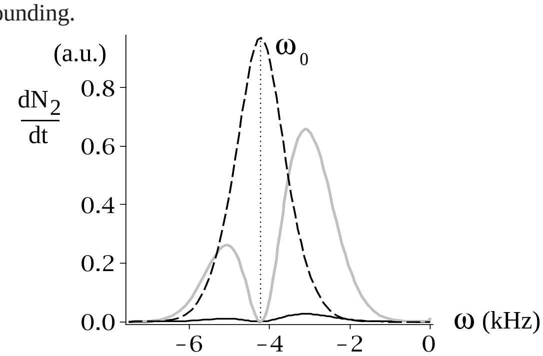

Figure 1: *Scattering rate of a bulk Bose condensed gas of ^{87}Rb for $\mathbf{q}^2/2m = 30$Hz. The black dashed/solid curve is the rate calculated in absence/presence of the screening. See the grey curve for a magnification of the black solid curve ($\times 25$). The superfluid fraction is 80% and $\epsilon_g = 4.3$kHz. In this process, atoms with an initial momentum $\mathbf{k}$ and energy $\epsilon_{1,\mathbf{k}} = \epsilon_g + \mathbf{k}^2/2m$ are transferred into a second level with momentum $\mathbf{k}+\mathbf{q}$ and energy $\epsilon_{2,\mathbf{k}+\mathbf{q}} = (\mathbf{k}+\mathbf{q})^2/2m$ provided $\omega = \epsilon_{2,\mathbf{k}+\mathbf{q}} - \epsilon_{1,\mathbf{k}}$. In absence of screening, a resonance appears at $\omega_0 = \mathbf{q}^2/2m - \epsilon_g$. The screening effect strongly reduces the Raman scattering and, in particular, forbids it for condensed atoms i.e. for $\omega = \omega_0$.*

[1] D.M. Stamper-Kurn et al., Phys. Rev. Lett. **83**, 2876 (1999).
[2] P. Navez, Physica A **387**, 4070 (2008); P. Navez, Physica A **356**, 241-278 (2005).

Feshbach Resonances in Bose-Fermi Cr Gas Mixtures

Z. Pavlović[1,2], H. R. Sadeghpour[2], R. Côté[1]

[1] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[2] *ITAMP - Center for Astrophysics, Cambridge, MA 02138, USA*

We report calculations of Feshbach resonances in ultra-cold boson-fermion Cr samples in an optical trap. For the ^{52}Cr-^{53}Cr and ^{53}Cr-^{53}Cr systems, the Feshbach resonances are driven by magnetic dipolar interaction in the ground state with a large magnetic moment, $6\mu_B$, and hyperfine interaction of strength $a_{\rm hf} = -83.6$ MHz. The formation of an extended class of magnetically tuned Feshbach resonances is predicted for both boson-fermion, boson-boson and fermion-fermion mixtures. The positions and widths of the resonances are determined from a full-scale coupled channel calculation, incorporating the dipole-dipole interaction, whose solutions are analytically extended using the quantum defect method for the $1/R^6$ potential[1]. The resulting scattering matrix is transformed[2] into the hyperfine representation and resonance information is extracted. The coupled channel bound state calculations are employed to monitor the progression of bound states into resonances as a function of applied magnetic field, also used for identification.

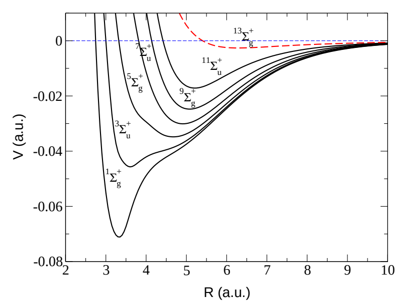

Figure 1: *Ab initio* Cr_2 Born-Oppenheimer potentials[3]

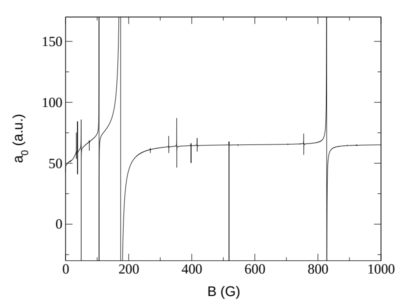

Figure 2: Calculated ^{52}Cr-^{53}Cr scattering length as a function of magnetic field (preliminary data)

[1] Bo Gao, Phys. Rev. A **58**, 1728 (1998)
[2] Bo Gao *et al.*, Phys. Rev. A **72**, 042719 (2005)
[3] Z. Pavlović *et al.*, Phys. Rev. A **69**, 030701 (2004)

Hydrodynamic excitations in a Bose-Einstein condensate

R. Meppelink, S. B. Koller, J. M. Vogels, P. van der Straten

Atom Optics and Ultrafast Dynamics, Utrecht University, The Netherlands

In our BEC of sodium atoms we have reached a record number of 250 million condensed atoms in a highly asymmetric potential of 96×1.5 Hz. This allows us to study the hydrodynamic regime. We define the hydrodynamicity as the ratio between the collision rate γ_{col} and the axial trap frequency ω_{ax}. In our experiment the hydrodynamicity is more than 10, which allows us to study the propagation of both first and second sound in the two-fluid model. As an initial step we have studied the out-of-phase oscillation of the condensate with respect to the thermal cloud, which is reminiscent to second sound in the case of liquid helium. If we consider the condensate as a superfluid, which flows through any obstacle without friction, one expects this motion to be undamped. By displacing the condensate with a shallow dipole trap with the respect to the thermal cloud, we have observed this out-of-phase oscillation. The frequency of the motion is shifted with respect to the trap frequency and most importantly becomes damped (see Fig. 1). We have measured the shift and damping under various experimental conditions. We observe a decrease of the damping for decreasing axial trap frequencies, which suggests that the damping will vanish in the uniform case. We will discuss the origin of the damping mechanism at the conference.

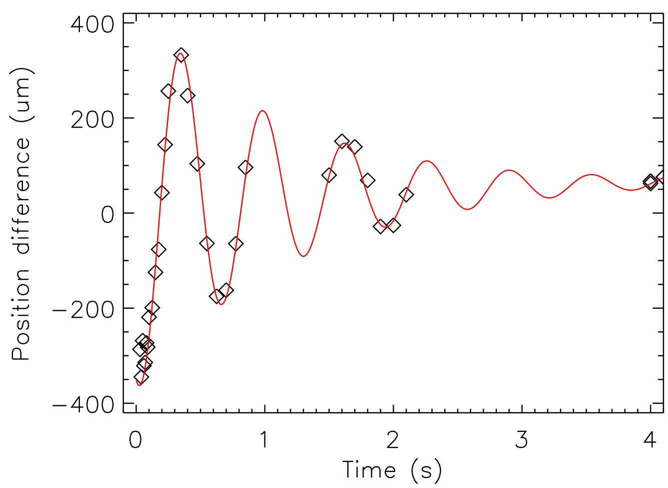

Figure 1: *Out-of-phase oscillation of the condensate with respect to the thermal cloud.*

Atom Interferometry with Interacting Bose-Einstein Condensates

R. G. Scott, T. E. Judd, T. M. Fromhold

School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

Recent experiments[1] have demonstrated that the relative phase Δ of two elongated Bose-Einstein condensates (BECs) can be inferred by merging them on an atom chip. This is done by monitoring the expanded combined cloud, which becomes broader as Δ approaches π. We show that this effect is due to the resonant production of a soliton, and its subsequent decay into vortices[2] (see Fig. 1). We tailor the performance of the interferometer by varying the merging time τ and temperature. Increasing the temperature broadens the resonance so that vortices are generated over a wider range of Δ. By characterising the function of the interferometer we identify the advantages of using interacting BECs, and discuss their potential applications as motion detectors and sensors of weak forces.

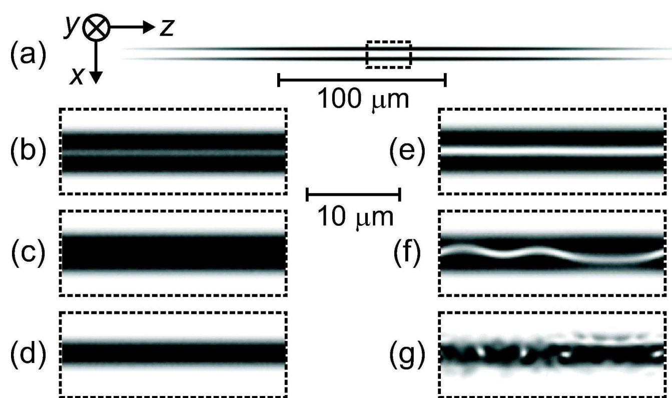

Figure 1: *(a) Atom density profile of the two BECs in the $y = 0$ plane (axes inset) at $t = 0$. (b)-(g) Density profiles within the region enclosed by the dashed rectangle in (a) at key stages of the merging process ($\tau = 5ms$) calculated for $\Delta = 0$ at $t = 3$ ms (b), 4 ms (c), 5 ms (d), and for $\Delta = \pi$ at $t = 3$ ms (e), 4 ms (f), and 5 ms (g). Upper [lower] horizontal bars show scales in (a) [(b)-(g)].*

[1] G.-B. Jo, J.-H. Choi, C. Christensen, T. Pasquini, Y.-R. Lee, W. Ketterle and D. Pritchard, Phys. Rev. Lett. **98** 180401 (2007)

[2] R.G. Scott, T.E. Judd and T.M. Fromhold, Phys. Rev. Lett. **100** 100402 (2008)

Virial expansion for ultracold trapped fluids and the exactness of the local density approximation

V. M. Romero-Rochín, N. Sandoval-Figueroa

Instituto de Física, Universidad Nacional Autónoma de México.
Apartado Postal 20-364, 01000 México, D.F. Mexico.

We derive the virial expansion of the grand potential for a fluid confined by an external field. The fluid may be classical or quantum and it is assumed that interatomic interactions are pairwise additive. We analyze several confining potentials and we find the appropriate "generalized" volume and pressure variables for each case that replace the usual volume and hydrostatic pressure. We emphasize that this treatment yields the correct equation of state of the fluid. As a corollary, we show that the so-called *local density approximation* is exact for these systems in the thermodynamic limit. We discuss the relevance of these findings in the description of the currently confined ultracold gases. We present explicit results for an ultracold gas confined by a quadrupolar potential within the Hartree-Fock approximation.

Dynamical evolution of an interacting Bose gas at low temperatures described through a quantum kinetic equation

R. Paredes, Y. Romero, R. Muñoz-Rodriguez

Instituto de Física, UNAM A.P. 20-364, México 01000 D.F. Mexico.

We study an interacting Bose gas at low temperatures confined in a harmonic potential in three dimensions. The system under study consists of N particles out of equilibrium distributed on the first κ energy levels of the ideal harmonic oscillator. By numerically solving the time-dependent Schrödinger equation for a few number of particles we first demonstrate that the system reaches thermal equilibrium through ellastic binary collisions. Then, based on a Boltzmann scheme, we derive the quantum kinetic equation that leads the system towards thermal equilibrium when pair interactions between particles are considered. We find that the system obeys two quantum kinetic equations for the occupation numbers n_κ, one for negative values of the chemical potential ($\mu < 0$) and other for the chemical potential equal to zero ($\mu = 0$). We also find that the kinetic equations satisfy total energy conservation for the N particles, and that it has as a stationary solution the Bose-Eisntein distribution. By numerically solving the coupled system of equations for each case ($\mu < 0$ and $\mu = 0$), we determine the evolution in time of the occupation number n_κ for each state.

Evolution and Measurement of Relative Phase in a Two-Component Bose-Einstein Condensate

R. Anderson, B. V. Hall, C. Ticknor, P. Hannaford, A. I. Sidorov

ARC Centre of Excellence for Quantum-Atom Optics and Centre for Atom Optics and Ultrafast Spectroscopy
Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

Knowledge of the phase of matter waves is of crucial importance for studies of interferometry, entanglement and precision measurement. We are studying the spatio-temporal evolution of the relative phase in a two-component Bose-Einstein condensate: the $|F=1, m_F=-1\rangle, |F=2, m_F=+1\rangle$ pseudo-spinor system of ^{87}Rb, using a micromagnetic trap on an atom chip. In addition to previous studies of phase measurement for two-component systems of cold thermal atoms[1], we are investigating two techniques involving (i) phase reconstruction using a spatially sensitive interferometric technique, and (ii) phase retrieval using a non-interofometric algorithm[2]. We prepare condensates in a superposition of the two spin states using a two-photon microwave-radiofrequency pulse of duration $\sim 1\,\mathrm{ms}$, and allow the system to evolve via nonequilibrium mean field dynamics for hundreds of milliseconds. We then observe the amplitude of each component by measuring the population of each spin state, with or without the addition of a second two-photon pulse (Ramsey technique). Our preliminary results show evolution of the relative phase along the direction of weak confinement (Fig. 1), consistent with mean field modelling. This work is important in the context of quantum technologies such as collisional phase gates for quantum information processing[3], and atomic clocks using trapped ultracold atoms. The role of mean field dynamics, phase diffusion and decoherence in these applications is yet to have detailed experimental investigation.

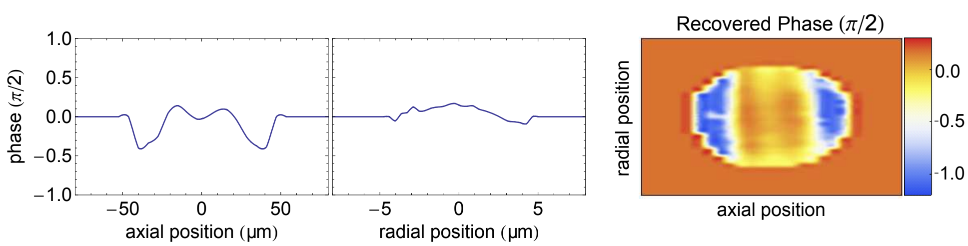

Figure 1: *Reconstructed relative phase of a two-component Bose-Einstein condensate after 90 ms of nonequilibrium mean field dynamics using an interferometric method.*

[1] J.M. McGuirk *et. al.*, Phys. Rev. Lett. **89**, 090402 (2002).
[2] Y.E. Tan *et. al.*, Phys. Rev. E **68**, 066602 (2003).
[3] P. Treutlein *et. al.*, Phys. Rev. A **74**, 022312 (2006).

Inelastic collision dynamics of ^{87}Rb spin-2 Bose-Einstein Condensates

S. Tojo, T. Hayashi, T. Tanabe, T. Hirano

Department of Physics, Gakushuin University, Tokyo 171-8588, Japan

We have experimentally investigated the dynamics of ^{87}Rb spin-2 Bose-Einstein condensates confined in an optical trap. Owing to its rich variety of internal degrees of freedom, many interesting dynamics can be observed. As well as elastic spin-exchange collisions, ^{87}Rb spin-2 condensates in the upper hyperfine level have large inelastic collision rates in comparison with those of lower hyperfine levels because of hyperfine-changing collisions[1,2]. Previously, the inelastic collision rates were roughly estimated under the condition in which spin-exchange collisions occurred, and only the loss rates of total number of atoms were estimated. It is primarily important to manifest mechanisms of inelastic collisions individually for each magnetic sublevel for the study of spin dynamics in multi-component condensates.

In this work, we have observed the time dependence of spin populations in spin-2 two-component condensates initially populated in several spin-states at 3 G of the magnetic field in which the spin-exchange collisions between different magnetic sublevels in the same hyperfine states were suppressed. Figure 1 depicts time-dependence of number of condensed atoms initially populated in (a) $m_F = -1$ and $m_F = -2$ states, and (b) $m_F = +1$ and $m_F = -2$ states with almost equal populations. We have also observed those of other spin-states; $m_F = 0$ and $m_F = -2$ states, $m_F = +2$ and $m_F = -2$ states, and $m_F = +1$ and $m_F = -1$ states. The results show that the inelastic collision rates depend on spin-states. The spin-dependent inelastic collision rates can be explained by corresponding collision channels[3].

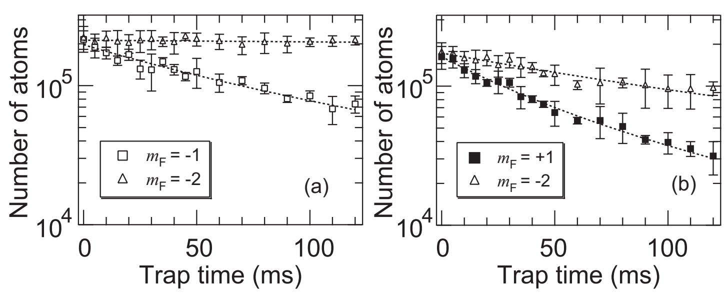

Figure 1: *Time-dependence of condensed atoms initially populated in $m_F = -1$ and $m_F = -2$ (a), and $m_F = +1$ and $m_F = -2$ (b).*

[1] T. Kuwamoto *et. al.,* Phys. Rev. A 69, 063604 (2004).
[2] H. Schmaljohann *et. al.,* Phys. Rev. Lett. 92, 040402 (2004).
[3] Y. Kawaguchi, H. Saito, and M. Ueda (private communication).

Optical Traps for ultracold metastable helium atoms

J. Simonet, J. Dugué, C. Buggle, M. Leduc

Laboratoire Kastler Brossel/ IFRAF, 24 rue Lhomond, 75231 Paris Cedex 05, France

One of the main characteristics of metastable helium atoms is their high internal energy (20 eV). This energy can be released when a metastable atom hits a surface, ejecting one electron. Therefore, using a Channeltron Electron Multiplier (CEM), one can detect atoms with a time resolution of up to 5 ns. However, this high internal energy raises the problem of inelastic Penning ionizations, following: $He^* + He^* \rightarrow He + He^+ + e^-$.
This process has a rate of the order of 10^{-10}cm^3.s^{-1} but is reduced by four orders of magnitude if the atoms are spin polarized due to total spin conservation.
We report on the progess of the set up of a dipole trap for ultracold metastable helium using a red detuned fiber laser at 1560nm. One of the aims of this optical trap is to release the constraint on the magnetic field value. We plan to measure the magnetic field dependance of inelastic collision rates initially calculated by P. O. Fedichev[1], for temperatures smaller than 10μK. In a spin polarized gas of helium, the spin-spin interaction produces spin relaxation (α_{rel}) and relaxation induced Penning ionization (α_i) if the polarization condition is no longer maintained.
We also present the development of a new generation of magnetic trap based on a clover leaf trap setup which is compatible with in situ loading of a condensed gas into a 3D optical lattice[2]. The coil geometry is designed to optimize optical access on 8 independant optical axes. We intend to monitor the Penning ionization rate in order to follow the real-time dynamics of the Superfluid-Mott insulator quantum phase transition.

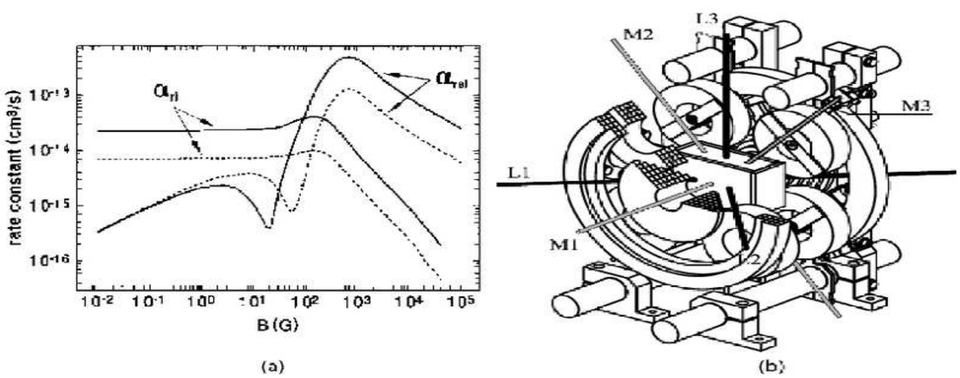

Figure 1: *(a) Rate constants α_{rel} and α_i. (b) Setup of the new magnetic trap.*

[1] P. O. Fedichev, M. W. Reynolds, U. M. Rahmanov and G. V. Shlyapnikov, *Phys. Rev. A* **53** 1447 (1996)
[2] C. Buggle, N. Zahzam, J. Dugué and M. Leduc, in preparation

Weightless Bose-Einstein Condensates

Y. P. Singh[1], T. van Zoest[1], W. Herr[1], N. Gaaloul[1], S. Seidel[1], E. M. Rasel[1], W. Ertmer[1], K. Bongs[2], T. Könemann[3], H. Müntinga[3], W. Brinkmann[3], C. Lämmerzahl[3], H. Dittus[3], E. Kajari[4], R. Walser[4], W. P. Schleich[4], A. Vogel[5], K. Sengstock[5], W. Lewoczko-Adamczyk[6], M. Schiemangk[6], A. Peters[6], T. Steinmetz[7], J. Reichel[7]

[1]*Institute for Quantum Optics, Leibniz University of Hannover, 30167 Hannover, Germany*
[2]*Midlands Ultracold Atom Research Centre, Birmingham B15 2TT, United Kingdom*
[3]*ZARM, University of Bremen, 28359 Bremen, Germany*
[4]*University of Ulm, Institute for Quantum Physics, 89081 Ulm, Germany*
[5]*University of Hamburg, Institute for Laser-Physics, 22761 Hamburg, Germany*
[6]*Institute for Physics, Humboldt University of Berlin, Germany*
[7]*Laboratoire Kastler Brossel de l'E.N.S. 75231 Paris, France*

Realization of a Bose-Einstein Condensate (BEC) in the year of 1995 has opened up a plethora of new possibilities to understand the fundamental questions such as quantum phase transitions, super fluidity, matter wave interference etc. The extremely low energy scales achieved in a typical earth-bound laboratory BEC has motivated us to continue the path towards lower energy scales by lifting Earth-bound laboratory restrictions. In particular microgravity offers several advantages for the fundamental research on cold quantum gases. First of all, it can provide an unperturbed evolution for long durations which is crucial for atom interferometers and atomic clocks. In a microgravity environment, the precision of these sensors can be extended by upto three orders of magnitude. Second it provides mass independent confining potential which is very important for the research on a mixture of quantum gases such as degenerate Fermi gases. Another important point is that in a microgravity environment, it is possible to adiabatically lower the trapping potential resulting in ultra-large condensates. The effect of ultra-weak long range forces become important in these condensates, which is expected to lead to new kinds of low energy phase transitions. More over it is possible to manipulate ultra-large condensates with a very high spatial resolution. In addition, microgravity is a prerequisite for fundamental tests in the quantum domain such as the equivalence principle or the realisation of ideal reference systems. A miniaturized and remote controlled facility to study BECs in the extended free fall at the drop tower in Bremen and during parabolic flights has been realized. The facility permits us to study the generation and outcoupling of BECs in microgravity, the study of decoherence and atom interferometry. For the first time, we report on the realization of Rb^{87} BECs and its subsequent evolution for as long as 1 second in a microgravity environment.

State selective single atom detection on a magnetic microchip

H. Bender, A. Günther, A. Stibor, J. Fortágh, C. Zimmermann

Quantum Optics Group, Institute for Physics, University of Tübingen, Auf der Morgenstelle 14, Tübingen, Germany

The possibility to detect small amounts of atoms on a magnetic microchip opens the door to a variety of interesting fundamental experiments in the field of ultracold quantum gases. Standard absorption imaging requires a minimum number of several hundred atoms. Thus novel detection methods with single atom sensitivity are currently developed.
Here, we present a single atom detector which is implemented in our magnetic microchip setup. The detection scheme is based on optical ionization of single atoms and subsequent counting of the ions in a channeltron. With this method a detection efficiency of 60% was achieved. We characterized the detector by ionizing a cloud of rubidium atoms at a temperature of about 10 μK in different combinations of magnetic and optical dipole traps on the microchip and with varying excitation laser power. Furthermore we were able to record in situ a complete hyperfine resolved two photon transition spectrum of a single cloud (see fig.1). It was also possible to selectively detect single atoms in different hyperfine groundstates. By additionally irradiating microwaves, the atoms could be ionized depending on their position within the magnetic trap according to their temperature. In that way the temperature distribution of the atoms in the magnetic trap could be determined.

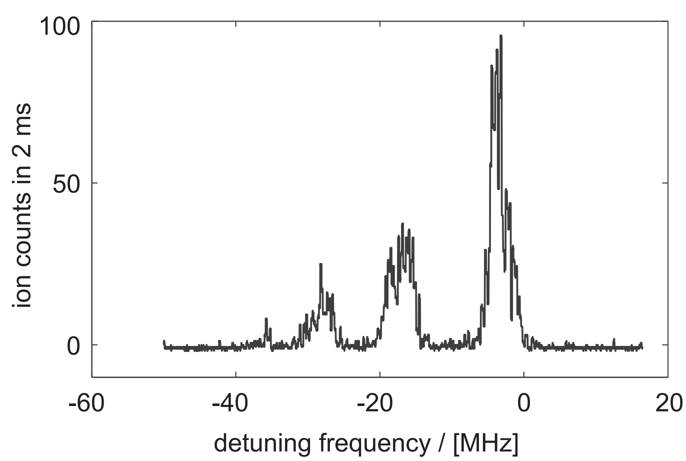

Figure 1: *Two photon transition between the 5 $S_{1/2}$, $F = 2$, and the four hyperfine levels 5 $D_{5/2}$, $F = 4...1$, recorded by state selective single atom laser ionization of a single ultracold cloud on an atom chip. The spectrum is scanned by detuning the frequency of the excitation laser.*

Bosonic Tonks-Girardeau Gases in a Split Trap

J. Goold, Th. Busch

Physics Department, University College Cork, Cork, Ireland

One-dimensional quantum gases in the strong correlation limit are interesting from an experimental as well as from a theoretical point. Apart from opening new avenues of exploration in physics, they are also highly amenable to theoretical treatment, allowing for detailed insight into many-particle physics.
In our work we have calculated the exact many-body properties of a bosonic Tonks-Girardeau gas confined in a harmonic potential with a tunable δ-function barrier at the trap center. This system is one of the few non-trivial examples where a mathematically exact solution for the density matrix can be found and from which, in turn, many interesting physical properties can be derived.
Here we show the dependence of the density, the pair distribution function, the momentum distribution, and the coherence as a function of barrier height for samples of up to 50 particles. We find, through diagonalization of the reduced single particle density matrix, that with increasing barrier height the coherence of the sample becomes an oscillating function of the particle number. This odd-even effect is shown to also manifest itself in both the momentum distribution and the visibility of the interference fringes at the end of free temporal evolution. Finally, we present an investigation into the entanglement inherent in split Tonks gas samples.

Vortex nucleation and non-equilibrium dynamics in a Bose-Einstein condensate at finite temperatures

T. M. Wright[1], R. J. Ballagh[1], A. S. Bradley[1,2], C. W. Gardiner[1], P. B. Blakie[1]

[1] *Jack Dodd Centre for Quantum Technology, Department of Physics, University of Otago, Dunedin, New Zealand*
[2] *ARC Centre of Excellence for Quantum-Atom Optics, School of Physical Sciences, University of Queensland, Brisbane, Australia*

Vortex nucleation and lattice formation in a rotationally stirred atomic Bose-Einstein condensate is intimately connected to the thermal behaviour of the Bose field[1,2,3], and thus provides an important testbed for dynamical theories of cold bosonic gases. A typical experiment[4] involves stirring a very cold condensate with an elliptically deformed rotating trap. Angular momentum, in the form of quantized vortices, is imparted to the condensate through its coupling to the non-condensed fraction. A non-condensed fraction may be formed by the excitation of dynamically unstable collective excitations of the condensate, leading to a highly excited state, far from equilibrium. The subsequent dissipative relaxation to an equilibrium state thus requires an analysis beyond a mean-field description, as recognised by a number of authors (e.g. [3]).
Here we present a model of vortex nucleation in a quasi-2D condensate initially at $T = 0$ and perturbed by a weakly anisotropic rotating trapping potential. In our approach the low energy dynamics of the Bose field are described using a classical field method in which the atom number and (rotating-frame) energy are conserved[5]. Our approach allows us to quantify the development of the thermal component, and determine its role in vortex nucleation and dynamics, during a strongly non-equilibrium process. We discuss methods of temporal analysis we have developed to characterise the field and identify the condensate in the presence of an irregular distribution of vortices, where traditional definitions[6] of Bose-condensation do not describe a single well-defined condensate mode. We show that turbulent superfluidic behaviour can be distinguished from thermal behaviour by analysing temporal correlations of the field. We also determine the thermodynamic parameters of the thermal component, and extract rates of excitation damping from the classical field trajectories.

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[2] C. Lobo et al., Phys. Rev. Lett. **92**, 020403 (2004).
[3] K. Kasamatsu et al., Phys. Rev. A **67**, 033610 (2003).
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[5] A. S. Bradley et al., Phys. Rev. A **77**, 033616 (2008).
[6] O. Penrose et al., Phys. Rev. **104**, 576 (1956).

Quantum Fluctuation Effect in Dynamical Instability of Bose–Einstein Condensate with a Highly Quantized Vortex

T. Sunaga[1], M. Mine[1], K. Misao[2], Y. Yamanaka[3]

[1]*Department of Physics, Waseda University, Japan*
[2]*Yukawa Institute for Theoretical Physics, Kyoto University, Japan*
[3]*Department of Electronic and Photonic Systems, Waseda University, Japan*

The Bose–Einstein condensation, which occurs in many-body quantum system, should ultimately be treated by the quantum field theory. There the quantum fields, describing quantum fluctuation, are usually expanded in terms of an appropriate complete set of wave functions corresponding to a quasi-particle picture. The Bogoliubov-de Gennes (BdG) equations whose eigenfunctions form such a complete set, are used for a number of theoretical works on the trapped Bose-Einstein condensates[1], and are known to give the energies of the quasi-particles when all the eigenvalues are real. The BdG equations can have complex eigenvalues in general, and the existence of complex modes is associated with the dynamical instability, that is, the decay of the initial configuration of the condensate[1]. In our previous work[2] we have developed a consistent formulation of the quantum field theory in the presence of complex eigenvalues of the BdG equations. We have given the complete set including complex modes and expanded the quantum field. It is then shown that the state space is an indefinite metric one and that the free Hamiltonian is not diagonalizable in the conventional bosonic representation. However, it is not clear yet how one should select quantum states (called physical states), reflecting the instability of the condensate. In order to study the instability, we have formulated the linear response of the density against the time-dependent external perturbation within the regime of Kubo's linear response theory. In this work, we examine several candidates of quantum states for a system with a highly quantized vortex. We find suitable physical states by numerical calculations, implying that they lead to the positive-definite fluctuation density and the time evolution of the density fluctuation representing the splitting from a highly quantized vortex to single vortices properly.

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Rydberg excitation of a Bose–Einstein condensate

Tilman Pfau, Rolf Heidemann, Ulrich Raitzsch, Björn Butscher, Vera Bendkowsky, Robert Löw

5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, D-70550 Stuttgart, Germany, t.pfau@physik.uni-stuttgart.de

Rydberg atoms provide a wide range of possibilities to tailor interactions in a quantum gas. Here we report on Rydberg excitation of Bose-Einstein condensed ^{87}Rb atoms. The Rydberg fraction was investigated for various excitation times and temperatures above and below the condensation temperature. The excitation is locally blocked by the van der Waals interaction between Rydberg atoms to a density-dependent limit. Therefore the abrupt change of the thermal atomic density distribution to the characteristic bimodal distribution upon condensation could be observed in the Rydberg fraction. The observed features are reproduced by a simulation based on local collective Rydberg excitations [1].

The excitation dynamics was investigated for a large range of densities and laser intensities and shows a full saturation and a strong suppression with respect to single atom behaviour. The observed scaling of the initial increase with density and laser intensity provides evidence for coherent collective excitation. This coherent collective behaviour, that was observed for up to several thousand atoms per blockade volume is generic for all mesoscopic systems which are able to carry only one single quantum of excitation [2].

Despite the strong interactions the evolution can still be reversed by a simple phase shift in the excitation laser field. We experimentally prove the coherence of the excitation in the strong blockade regime by applying an optical rotary echo technique to a sample of magnetically trapped ultracold atoms, analogous to a method known from nuclear magnetic resonance. We additionally measured the dephasing time due to the interaction between the Rydberg atoms [3].

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[2] R. Heidemann, U. Raitzsch, V. Bendkowsky, B. Butscher, R. Löw, L. Santos, T. Pfau "Evidence for coherent collective Rydberg excitation in the strong blockade regime" Phys. Rev. Lett. **99**, 163601 (2007).

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A high flux source of magnetically guided ultracold chromium atoms

Tilman Pfau, Alex Greiner, Jimmy Sebastian, Anoush Aghajani-Talesh, Markus Falkenau, Axel Griesmaier

5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, D-70550 Stuttgart, Germany, t.pfau@physik.uni-stuttgart.de

BEC production is typically performed by a time sequence of cooling steps leading to an average yield of 10^6 to $10^7 atoms/sec$ for the best alkali experiments and $10^3 atoms/sec$ for chromium BEC [1]. Considerable effort has been invested into the concept of a truly cw atom laser based on a magnetic guide which is loaded with ultracold atoms. The highest reported flux of magnetically guided alkali atoms approaches 7 $10^9 atoms/sec$ [2].

Due to the high magnetic moment, chromium atoms are particularly well suited for magnetic guiding. As the required magnetic field gradients are well compatible with gradients required for a magneto-optical trap (MOT) a moving molasses MOT can be installed in the guide for loading without mode matching problems. The MOT is fed by a Zeeman slower.

We observe a flux of up to 6 10^9 chromium atoms at a velocity of 6.2 m/sec. The velocity could be tuned by the frequency difference between the molasses beams between 2 and 20 m/sec. The guide was made of four current carrying wires separated by 4.6 cm leading to a magnetic gradient of 13 G/cm. Downstream the guided beam is radially compressed by reducing the wire distance to 9 mm and a gradient of 355 G/cm. In this area the flux and the temperature of the beam was measured by laser induced fluorescence. Radial and longitudinal temperatures were 1-2 mK in the compression zone. The beam will serve as an intense source of cold atoms to load an optical dipole trap (ODT) continuously. Future experiments are heading towards the demonstration of a high flux cw atom laser.

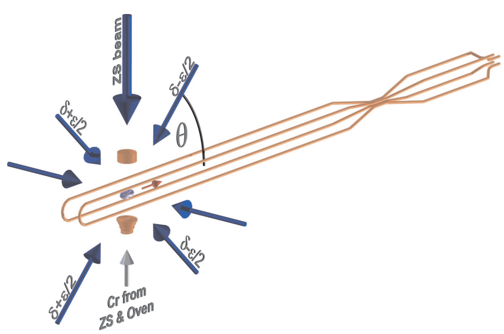

Figure 1: *Magnetic guide for ultracold chromium atoms. The total length of the guide is 1.4* m.

[1] A. Griesmaier, J. Werner, S. Hensler, J. Stuhler and T. Pfau, Phys. Rev. Lett. **94**, 160401 (2005).

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Controlled entanglement of spin and motional state of a Bose-Einstein condensate on a microwave atom chip

P. Böhi[1,2], M. Riedel[1,2], J. Hoffrogge[1,2], T. W. Hänsch[1,2], P. Treutlein[1,2]

[1]*Ludwig-Maximilians-Universität, München, Germany*
[2]*Max-Planck-Institut für Quantenoptik, Garching, Germany*

We report on an experiment in which we use spin-dependent micropotentials to manipulate the quantum state of Bose-Einstein condensates (BECs) on an atom chip. The potentials are generated by a combination of static magnetic and microwave near-fields in the proximity of on-chip microwave guiding structures. Microwave dressing of hyperfine states allows us to adjust the spin-dependence of the potentials.[1]
We prepare a ^{87}Rb BEC in a superposition of the two internal spin states $|0\rangle \equiv |F = 1, m = -1\rangle$ and $|1\rangle \equiv |F = 2, m = 1\rangle$ and use the spin-dependent potentials to split and recombine the corresponding motional wave functions (see Fig. 1). Ramsey interferometry is used as a probe of the dynamics. The splitting process entangles the spin and motional quantum state of the atoms in a controlled way and leads to a collapse of the Ramsey interference contrast. After recombining the wave packets of the two spin states we observe a revival of the interference fringes, which shows that the manipulation is coherent.
The spin-dependent splitting process is a key ingredient for atom chip quantum gates, which rely on collisions in a spin-dependent potential to generate entanglement between atoms.[1,2] It could furthermore be used to study interaction-induced effects such as phase diffusion and entanglement in small BECs.

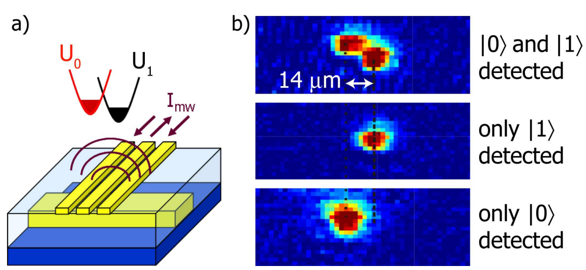

Figure 1: *Spin-dependent spatial splitting of a BEC with microwave near-field potentials. (a) Atom chip layout with microwave guiding structure. Potential U_i for internal state $|i\rangle$ $(i = 0, 1)$ is sketched. (b) Absorption images of BECs in a superposition of the spin states $|0\rangle$ and $|1\rangle$ after splitting the corresponding wave functions with the microwave potential. Top: both states are imaged. Center: only state $|1\rangle$ is imaged. Bottom: only state $|0\rangle$ is imaged.*

[1]P. Treutlein, T. W. Hänsch, J. Reichel, A. Negretti, M. A. Cirone, and T. Calarco, Phys. Rev. A **74**, 022312 (2006).
[2]P. Treutlein *et al.*, Fortschr. Phys. **54**, 702 (2006).

The splitting two-fluid hydrodinamic equations for Bose–Einstein condensate

V. I. Tsurkov[1,2]

[1] *Georgia Southwestern State University, Americus, GA 31709, USA*
[2] *Computing Center of RAS, Moscow, 119991, Russia*

The subject of the consideration is the set of two-fluid hydrodinamic equations (see, for example[1,2])

$$\partial\rho/\partial t + \partial(\rho_s v_s + \rho_n v_n)/\partial x = 0, \quad \rho = \rho_s + \rho_n,$$

$$\partial(\rho_s v_s + \rho_n v_n)/\partial t + \partial(\rho_s v_s^2 + \rho_n v_n^2)/\partial x + \partial p/\partial x = 0,$$
$$\partial v_s/\partial t + \partial(v_s^2/2 + \mu)/\partial x = 0,$$
$$\partial S/\partial t + \partial(S v_n)/\partial x = 0,$$

where t is the time, x is the spatial coordinate, ρ is the density, S is the entropy per unit volume, $\rho_s\backslash\rho_n$ and $v_s\backslash v_n$ are the superfluid \ normal density and velosity respectively, μ is the chemical potential, p is the pressure.

We use these equations for the degenerate ideal Bose gas (see, for example,[3]). Then ρ_n is proportional to S. The equation of state is $p = BS^{5/3}$ (B — const). Ignoring at first the dependence of μ on $|v_s - v_n|$ according to the methodology[1], we obtain finally two splitting pairs of equations with respect to the variables v_n, S, and v_s, $R = (\rho - AS)$, where A is the constant

$$\partial v_n/\partial t + v_n \partial v_n/\partial x + (\partial p/\partial S)(S)^{-1}\partial S/\partial x = 0,$$

$$\partial S/\partial t + S\partial v_n/\partial x + v_n \partial S/\partial x = 0,$$

and

$$\partial v_s/\partial t + v_s \partial v_s/\partial x = 0,$$
$$\partial R/\partial t + R\partial v_s/\partial x + v_x \partial R/\partial x = 0.$$

The coupled equations are more complicated in general case when μ depends on the small value $|v_s - v_n|$.

The main results are unstable sharp peak density solutions of the initial value problems with respect to small perturbations and singular solutions of the Riemann problem by analogy to [4,5,6].

[1] I.M. Khalatnikov, "An introduction in the Theory of Superfluidity", W.A. Benjamin, New-York (1965).
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Effect of various time dependent longitudinal traps on Bose-Einstein condensate

Utpal Roy[1], S. Sree Ranjani[2], P. K. Panigrahi[3], A. K. Kapoor[2]

[1] *Dipartimento di Fisica, Università di Camerino, I-62032 Camerino, Italy*
[2] *School of Physics, University of Hyderabad, Hyderabad 500061, India*
[3] *Indian Institute of Science Education and Research (IISER) Kolkata, Salt Lake, Kolkata 700106, India*

The temporal variation of non-linearity coefficient or the transverse trapping potential produces Faraday waves [1], which is recently observed [2] in a cigar-shaped Bose-Einstein condensate (BEC) involving Bogoliubov modes. In this work, we study the effect of various longitudinal trap variations in BEC. The solution of the Gross-Pitaevskii equation with time dependent parameters results a stationary Schrödinger eigen value equation, where the constant part of the potential acts as the eigen value [3]. A number of variations in the oscillator frequency can be analytically incorporated. We study both sinusoidal and transient variations of the longitudinal trap frequency on BEC profile. The transient variations include hyperbolic cotangent functions and delta kicks [4]. We observe amplification, spreading of the BEC profile and various center of mass motions, resulting coherent control of cigar-shaped BEC.

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Noise and correlation measurements using single atom detection

V. Krachmalnicoff[1], D. Boiron[1], A. Perrin[1,2], H. Chang[1,3], M. Schellekens[1], V. Leung[1], J.-C. Jaskula[1], A. Aspect[1], C. I. Westbrook[1]

[1]*Laboratoire Charles Fabry de l'Intitut d'Optique, CNRS, Univ Paris-Sud, Campus Polytechnique RD128 91127 Palaiseau, France*
[2]*Atominstitut der Österreichischen Universitäten, TU Wien, A-1020 Vienna, Austria*
[3]*National Time Service Center, Laboratory of Frequency and Time Standards, 3, Shuyuan DongLu, Lingtong, 710600 Xi'an P.R.China*

In this poster we will present the creation of correlations between the atoms scattered during the collision of two Bose-Einstein condensates of metastable helium atoms [1] . The detection of the atoms and the measurement of the second order correlation function is performed with a single atom 3D detector based on a micro-channel plate with a delay line anode. We show that atoms of opposite momenta (in the center of mass frame) as well as atoms of collinear momenta are correlated. The back to back correlation corresponds to the formation of atomic pairs and is a consequence of the elastic scattering of two atoms of initial well defined momenta. The collinear correlation is related to the bosonic bunching of randomly scattered atoms which is the Hanbury Brown Twiss effect. We show that in both cases the correlation lengths are related to the momentum distribution of the colliding condensates. The correlation functions we observe lend to a study of the violation of classical inequalities and of a reduction of atom number fluctuations.

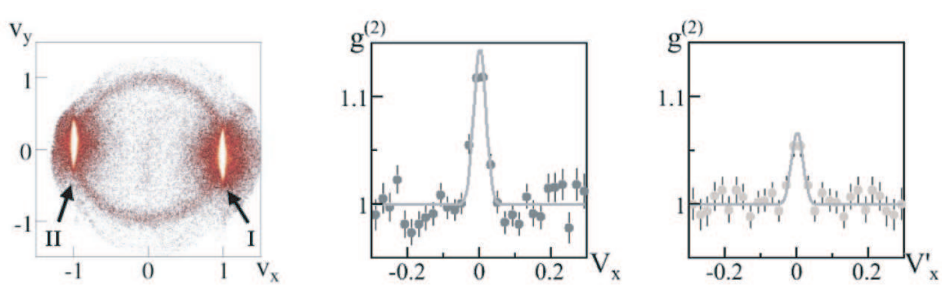

Figure 1: *a) Slice of the scattering sphere. The two colliding condensates (I and II) and the scattering shell are visible. b,c) Back to back and collinear correlation function along the long axis of the trapped condensate.*

[1]A. Perrin et al, "Atom-atom correlations in spontaneous four wave mixing of two colliding Bose-Einstein Condensates" Phys. Rev. Lett., Vol. 99, 150405, 2007.

Bose Condensates with Small s-wave Scattering Lengths: Effect of Dipolar Interaction

Y. P. Chen[1], D. Dries[2], J. Hitchcock[2], R. G. Hulet[2]

[1]*Department of Physics and Birck Nanotechnology Center, Purdue University, West Lafayette IN 47907 USA*
[2]*Department of Physics and Astronomy and Rice Quantum Institute, Rice University, Houston TX 77005 USA*

Using a variational approach, we have calculated the *in-situ* size and time-of-flight (TOF) expansion of a cylindrically symmetric Bose-Einstein Condensate (BEC) when the s-wave scattering length (a_s) is close to zero (which can be realized via, for example, a Feshbach resonance). We have specifically investigated the effect of dipolar interactions when the magnetic moment of the atoms is nonzero, and examined the dependence of the dipolar effect on the number of atoms, trap geometry and a_s. For a ^{52}Cr BEC, we obtain quantitative agreement with observations in recent experiments [1], and predict a collapse due to dipolar interaction to occur at positive a_s ($\sim$14$\pm$1a_o, using parameters similar to those in [1]). We have also performed calculations for BECs of alkali atoms, where the dipolar interactions are much weaker than in ^{52}Cr. We will show how our calculations may help measure small a_s and locate the zero- crossings. [1] T. Lahaye *et al.*, Nature **448**, 672 (2007); J. Stuhler *et al.*, Phys. Rev. Lett. **95**, 150406 (2005)

Holographic Storage of Multiple Coherence Gratings in a Bose-Einstein Condensate

Y. Yoshikawa[1,2], K. Nakayama[2], Y. Torii[1,2], T. Kuga[1,2]

[1] *Institute of Physics, University of Tokyo, Japan.*
[2] *PREST, CREST, Japan Science and Technology Agency, Saitama, Japan.*

Recently, the conversion of quantum state between atoms and photons has been an important subject in the field of quantum information processing. However, the number of modes for the atom-photon conversion per atomic cloud was limited to one in the previous works. Here, in this poster, we report a novel technique capable of multiplexed storage of atomic coherence and independent conversion to photons in a single atomic cloud. We also performed the proof-of-principle experiment using superradiant Raman scattering in an elongated cloud of Bose-Einstein condensate[1].

Figure 1(a) and (b) show an experimental setup and an energy-level diagram, respectively. A rubidium condensate in the state $|1\rangle$ is first irradiated by an off-resonant "write" beam, and a small fraction of atoms is coherently transferred to the state $|2\rangle$ by emitting σ^+-polarized anti-Stokes photons along the long axis of the condensate. Then, an atomic coherence grating with a corresponding recoil wave vector is created in the atomic cloud. To convert the grating to photons, another "read" beam is applied to the atoms. When the read beam is counter-propagating to the write beam (to satisfy the Bragg condition), it diffracts off the grating in a superradiant way and σ^--polarized Stokes photons are emitted along the opposite direction to the anti-Stokes photons [Fig. 1(c)]. By contrast, when the read beam is not counter-propagating, Stokes process is strongly suppressed owing to the phase mismatching, and the grating is kept stored in the cloud [Fig. 1(d)]. Using this Bragg selectivity, multiplexing of the write-read process can be realized by applying two phase-matched write-read beam pairs [Fig. 1(e)].

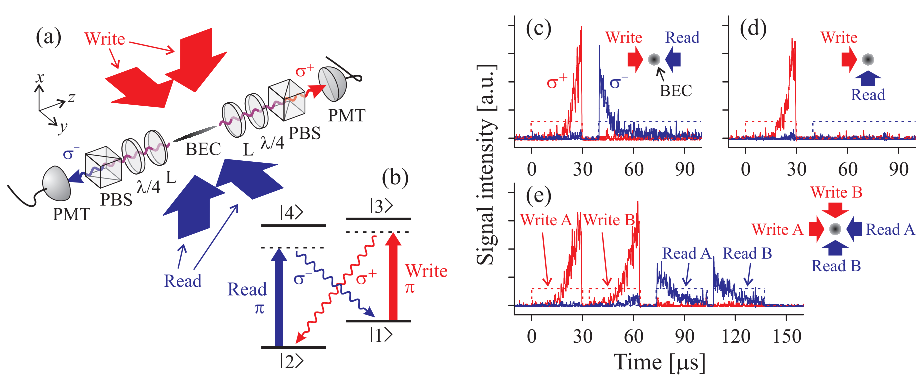

Figure 1: *(a) Experimental setup and (b) energy-level diagram. (c)-(e) show the observed waveforms of the scattered photons for various write-read configurations.*

[1] Y. Yoshikawa *et.al.* Phys. Rev. Lett. **99**, 220407 (2007).

Gross-Pitaevskii equation for a BEC of polarized molecules: anisotropic mass

A. Derevianko

Department of Physics, University of Nevada, Reno, Nevada 89557,USA

So far the theory of Bose-Einstein condensates (BEC) of polarized molecules was based on an ad hoc generalization of equations for spherical atoms. Here I adopt a rigorous approach to tunable low-energy dipolar interactions[1] and derive a non-linear mean-field Schrödinger equation for a harmonically-trapped condensate of polarized dipoles. I arrive at the following dipolar GPE for a condensate wavefunction Ψ

$$\left(-\frac{\hbar^2}{2M}\mathbf{\Delta}+U\left(\mathbf{r}\right)+g_0\left|\Psi\left(\mathbf{r}\right)\right|^2\right)\Psi\left(\mathbf{r}\right)+g_d\left(\frac{\partial^2}{\partial z^2}\left|\Psi\left(\mathbf{r}\right)\right|^2\right)\Psi\left(\mathbf{r}\right)=\mu_0\Psi\left(\mathbf{r}\right).$$

The derivative is taken along the polarizing field. The newly introduced coupling constant g_d is proportional to the off-diagonal scattering length characterizing mixing of s and d partial waves by the non-spherical dipolar collision process.

The corresponding result for the energy functional suggests introducing effective mass along the polarizing field,

$$M_{zz}^{\mathrm{eff}}\left(\mathbf{r}\right)=M/(1-8g_dM\,n\left(\mathbf{r}\right)/\hbar^2)\,,$$

where the number density $n(r)=|\Psi(r)|^2$. The mass remains "bare" (M) for the motion perpendicular to the polarizing field. Effectively, the dipolar interactions alter molecular mass. The resulting effective mass is anisotropic: to the leading order the mass is altered only for the motion along the polarizing field. For a typical BEC of alkali-metal atoms the effective mass is reduced by 10% from it's bare value. For molecules, the mass may be reduced by a factor of 1,000.

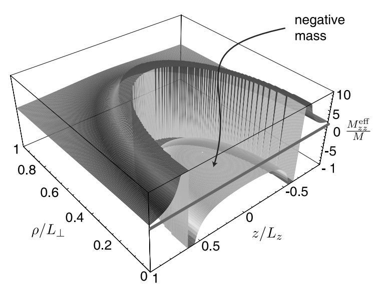

Figure 1: *Effective anisotropic mass $M_{zz}^{\mathrm{eff}}(\mathbf{r})$ as a function of position for a condensate cloud in a harmonic trapping potential. The BEC is mechanically unstable in the region of negative effective mass.*

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Feshbach Resonances in ultracold ^{40}K + ^{87}Rb mixture

S. Banerjee, M. Gacesa, P. Pellegrini, R. Côté

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

We report a theoretical study of Feshbach resonances in a ^{40}K + ^{87}Rb mixture at ultracold temperatures using accurate interaction potentials[1] in a full quantum-mechanical coupled channel calculation. Feshbach resonances in the initial collision open channel ^{40}K($f = 9/2$, $m_f = -9/2$) + ^{87}Rb ($f = 1$, $m_f = 1$) are found to agree with previous measurements, leading to precise values of the singlet and triplet scattering lengths for the system. We predict additional Feshbach resonances within experimentally attainable magnetic fields for other collision channels, and propose a realistic scheme for formation of stable ultracold KRb molecules using Feshbach-optimized photoassociation (FOPA)[2].

[1] A. Pashov et al., Phys. Rev. A **76, 022511 (2007)**
[2] P.Pellegrini et. al., Arxiv. Article ID 0806.1295

Singly excited doublet $^7Li_2 + {}^7Li$ potential energy surface for the formation of ultracold trimers

Jason N. Byrd, H. Harvey Michels, R. Côté

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

With the success of ultracold molecular formation among the alkali metals over the last few years, the dynamics of molecules in an ultracold trap has become an important topic of interest to many physicists. Both heteronuclear and homonuclear Lithium diatoms have been formed in the ground electronic state with great success using combinations of photoassociation and Feshbach resonances. Furthermore, recent theoretical proposals[1] have shown an efficient production of diatoms in the deepest vibrational states, thus allowing true ground state collisions. Recent theoretical studies of the spin aligned quartet ground state collisional process in both high vibrational states[2] and deeply bound vibrational states[3] have been done. To study the formation of ultracold trimers using photoassociation, accurate long and short range potential energy surfaces must be known. However, to date the study of the excited Lithium trimer has been restricted to only short ranges[4].
We present initial potential energy surface calculations of the excited Lithium trimer in the doublet state, $Li_2[X^1\Sigma_g^+]+Li[^2P_u]$, at both long and short ranges. The first ab initio surface to be calculated is the $^2A''$ surface with C_s symmetry, which can be extended to C_{2v} and $C_{\infty v}$ geometries for spectroscopic considerations. After which the $^2A'(2)$ states will be calculated giving the complete singly excited potential energy surface. The transition moments between the excited and ground doublet state are also calculated for each state. This surface and the corresponding transition moments will be used to calculate the scattering properties of the excited doublet state for both elastic and inelastic collisions. In addition to the scattering properties, the Feshbach resonances will also be calculated for the study of photoassociation production of ultracold $^7Li_3$.

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[3] Marko T. Cvitaš, et al, J. Chem. Phys. **127**, k 074302 (2007)
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Two-photon femtosecond photoassociation – better perspectives for coherent control?

C. P. Koch

Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin

Photoassociation (PA) has emerged as a technique to create ultracold molecules in their electronic ground state. Since it requires in principle only the presence of optical transitions, PA presents itself as an ideal candidate for coherent control with short shaped laser pulses. First attempts at femtosecond PA were, however, hampered by what seemed to be technical difficulties[1]. Indeed, the broad bandwidth of femtosecond lasers appears to be an obstacle for PA rather than a tool for control: Only a small band of transition frequencies close to the atomic resonance contribute significantly to the PA yield, while at the same time, excitation of the atomic resonance needs to be avoided. Theoretically, picosecond pulses in a pump-dump scheme were suggested[2], since their bandwidth is better adapted to PA. However, picosecond pulse shaping has yet to be developed.

A non-resonant two-photon process might resolve the ostensible conflict of driving a narrow-bandwidth transition by a broad-bandwidth laser[3]. For excitation with more than one photon, constructive and destructive interferences can be achieved for different pathways of the field, in addition to the different pathways which the molecule can take. While two-photon absorption may pave the way toward coherent control of PA, the success of the scheme will ultimately depend on the involved electronic states and transition frequencies. Here we discuss the perspectives of two-photon femtosecond PA for alkali and alkaline earth metal dimers.

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[2] C.P. Koch, E. Luc-Koenig, F. Masnou-Seeuws, Phys. Rev. A **73**, 033408 (2006).

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Spectroscopy of Ultracold ^{41}K^{87}Rb Molecules using Resonance Enhanced 2-photon Ionization

D. Akamatsu[1], K. Aikawa[1], M. Hayashi[1], J. Kobayashi[1], T. Kishimoto[2,3], K. Noda[1], M. Ueda[2,4], S. Inouye[1,2]

[1]*Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*
[2]*ERATO Macroscopic Quantum Control Project, JST, Yayoi, Bunkyo-ku, Tokyo, Japan*
[3]*The University of Electro-communications, Chofu, Tokyo, Japan*
[4]*Department of Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*

Ultracold polar molecules have attracted enormous interest for various applications such as quantum computation, ultracold chemistry, and elementary particle physics. One of the promising ways to create such ultracold molecules is to start with laser cooled atoms, associate them with Feshbach resonance and transfer them to the absolute ground state with Stimulated Raman Adiabatic Passage (STIRAP). To efficiently convert Feshbach molecules into abolute ground state moleules, finding a proper intermediate state is essential. Thus we set up an experiment to study Frank Condon factors between ground and excited states using ultracold molecules.
We start with a double species MOT of ^{41}K and ^{87}Rb, and photoassociate K and Rb by shining a laser beam red detuned from Rb D_1 line. In order to increase the photoassociation rate, we developed CMOT (Compressed-MOT) process, which simultaneously cools and compresses both clouds. Measured densities and temperatures were 2×10^{11} cm^{-3}and 400 μK for K and 4×10^{11} cm^{-3}and 100 μK for Rb, respectively. The photoassociated molecules radiatively decay to both singlet $X^1\Sigma^+$ and triplet $a^3\Sigma^+$ ground states. These molecules are ionized through resonance enhanced 2-photon ionization. Here 10ns-pulses from a dye laser with 10 Hz repetition rate were used. The ionized molecules are detected with a Channeltron. The spectrum of the vibrational energy levels were obtained with scanning the excitation frequency. The experimentally obtained energy levels match with those from *ab initio* calculations.
The increase in phase space density which is attained with the CMOT stage is also quite useful for an experiment aimed for quantum degeneracy. For example, recently we have successfully produced a BEC of 2×10^5 ^{41}K via evaporative cooling. It is known that ^{41}K and ^{87}Rb has several Feshbach resonances at low field. Thus once a proper transition for STIRAP is identified, the quantum degenerate mixture of ^{41}K and ^{87}Rb should serve as a good starting point from producing ultracold polar molucules.

Time-Domain Measurement of Spontaneous Vibrational Decay of Magnetically Trapped NH

H.-I Lu[1,2] W. C. Campbell[3,2], G. C. Groenenboom[4], E. Tsikata[3,2], J. M. Doyle[2,3]

[1]*School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA*
[2]*Harvard-MIT Center for Ultracold Atoms, Cambridge, MA 02138, USA*
[3]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[4]*Theoretical Chemistry, Institute for Molecules and Materials (IMM), Radboud University Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands*

The $v = 1 \to 0$ radiative lifetime of NH($X^3\Sigma^-, v = 1, N = 0$) is determined to be $\tau_{\mathrm{rad,exp.}} = 37.0 \pm 0.5_{\mathrm{stat}} {}^{+2.0}_{-0.8}{}_{\mathrm{syst}}$ ms ms, corresponding to a transition dipole moment of $|\mu_{10}| = 0.0540^{+0.0009}_{-0.0018}$ D. To achieve sufficiently long observation times, NH($X^3\Sigma^-, v = 1$) radicals are magnetically trapped using helium buffer-gas loading. The rate constant for background helium-induced collisional quenching was determined to be $k_{v=1} < 3.9 \times 10^{-15}$ cm^{3}s^{-1}, which yields the quoted systematic uncertainty on $\tau_{\mathrm{rad,exp.}}$. With a new *ab initio* dipole moment function and a Rydberg-Klein-Rees potential, we calculate a lifetime of 36.99 ms, in agreement with our experimental value.

A High Flux Continuous Source of Guided Polar Molecules

D. Patterson, J. Rasmussen, J. M. Doyle

Harvard University, Cambridge, MA 02138 USA

A high flux cold guided source for translationally and rotationally cold molecules and atoms has been demonstrated. Building on our earlier work to create cold beams, we have been able to guide polar molecules (ND_3), separating them from a buffer gas of cold helium or cold neon. Continuous guided fluxes of 10^{11} molecules/second and unguided fluxes of more than 10^{14} molecules/second, with forward velocities in the range of 50-150 m/sec, have been achieved. Possible applications for this general, high flux beam source will be presented, including collisional studies, loading magnetic and electrostatic traps, and applications to precision measurement.

Microwave Trapping of Buffer Gas Cooled Molecules

D. R. Glenn, J. F. Barry, D. M. Farkas, A. C. Vutha, J. A. Petricka, D. DeMille

Department of Physics, Yale University, New Haven, CT 06511, USA

We describe progress towards the realization of a proposal[1] to capture cold Strontium Oxide (SrO) molecules in a high power microwave trap. Our proposed protocol for producing ultracold molecules is outlined schematically in Fig.1. Laser ablation of solid precursor [A] yields a molecular vapor in a buffer gas cell. The molecules are cooled in their translational and internal degrees of freedom by thermalization with 4.2 K helium buffer gas [B]. Part of the thermalized sample is extracted from aperture [C] in the cell wall. An electrostatic quadrupole guide [D] transports the rotationally excited $|J = 1, 2; m = 0\rangle$ states of the Boltzmann distribution to a differentially pumped UHV trapping region. Upon reaching the trap volume, molecules are continuously transferred into the trapped rotational ground state $|J = 0; m = 0\rangle$ using a dissipative optical pumping process [E]. The trapped molecules [F] are then cooled sympathetically (by collisions with ultracold atoms in an overlapping MOT, not shown) or evaporatively.

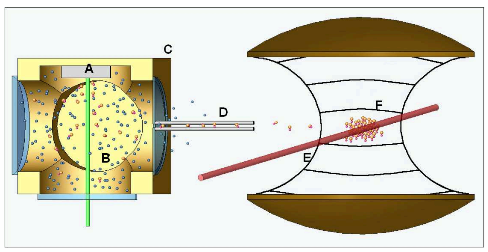

Figure 1: *Schematic of Cooling Procedure*

We present data that shows an ablation yield of $\sim 10^{12}$ molecules per pulse. Molecular fluorescence measurements of the beam flux indicate that an extraction efficiency of $\sim 10^{-3}$ can be attained in the effusive flow regime with an appropriate aperture. Data demonstrating transverse beam confinement by the electrostatic quadrupole guide are also shown. We obtain a flux enhancement factor of about 2.5 (averaged over all guided rotational states) for a guide of 10 cm length, consistent with numerical simulations. In addition, we present the results of a numerical calculation to determine the efficiency of the continuous dissipative loading scheme. For our guide geometry and a molecular beam with 4.2 K forward kinetic energy, a trap-loading efficiency of about 5×10^{-3} should be attainable. Finally, we describe measurements on microwave trap prototypes and outline the final cavity design. We have demonstrated resonator quality factors $Q \sim 5 \times 10^{-4}$, and have determined that 1.2 kW of input power can be dissipated while holding the mirror temperatures below $70\,^{\circ}\mathrm{C}$. Given these parameters, it should be possible to attain trap depths of $\sim$1.1 K for SrO. This work is supported by the ARO and the NSF.

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Towards Ultracold Mixtures and Molecules of Lithium and Ytterbium Atoms

A. Hansen, A. Khramov, J. Smith, W. Willcockson, W. English, R. Weh, S. Gupta

Department of Physics, University of Washington, Seattle, WA 98195

Exquisite control of interactions between ultracold atoms is now possible using scattering resonances. Ultracold diatomic molecules can also be formed using Feshbach and photoassociation resonances. Applying these methods between two different atomic species can lead to novel quantum phases of matter. These include Fermi superfluids with mass imbalance and strongly dipolar molecular superfluids. Further, stable ultracold dipolar molecular samples are promising systems for precise tests of fundamental symmetries and time variations of fundamental constants. We will report on progress towards building a system of ultracold lithium and ytterbium atoms to achieve these goals.

Ultracold Production and trapping of ultracold RbCs molecules

Eric R. Hudson[1], Nathan B. Gilfoy[1], St. Falke[1], C. D. Bruzewicz[1], S. Kotochigova[2], D. DeMille[1]

[1]*Department of Physics, Yale University, 217 Prospect Street, New Haven, CT 06511, USA*
[2]*Department of Physics, Temple University, Philadelphia, PA 19122, USA*

The electric dipole-dipole interaction provides a strong, long-range, tunable anisotropic interaction between polar molecules. This is fundamentally different from most interactions studied between ultracold atoms, which are typically isotropic and comparatively short-ranged. Features of the dipole-dipole interaction can lead to many novel and exciting phenomena, such as long-range topological order[1], quantum chemistry[2], and the possibility for quantum computation[3]. Furthermore, the presence of closely spaced internal levels of the molecules, *e.g.* Ω-doublet, rotational, and vibrational levels, presents a host of new possibilities for precision measurement of fundamental physics[4]. A trapped *ultracold* sample of polar molecules, which will provide high densities and long observation times, is thus a necessary step for observing these phenomena.

We have recently confined ultracold RbCs molecules in an optical lattice trap[5]. Currently, these molecules are in high-lying vibrational levels of the $a^3\Sigma^+$ electronic ground state. Inelastic collision rates of these molecules with both Rb and Cs atoms have been determined for individual vibrational levels, across an order of magnitude of binding energies. A simple model for the collision process is shown to accurately reproduce the observed scattering rates.

We are currently implementing an improved version of a population transfer process, previously demonstrated in our lab with pulsed lasers[6], to transfer trapped molecules from the $a^3\Sigma^+$ state into the $X^1\Sigma^+(v=0)$ absolute ground state. This state possesses a large electric dipole moment ($\mu \approx 1.3$ Debye). By this method, we expect to trap a sample of $> 10^4$ absolute ground state polar molecules ($X^1\Sigma^+$(v = 0; J = 0)) at a temperature of $\sim$20 μK and density of $\geq 10^9$ cm^{-3}. These molecular temperatures and densities should allow the observation of many of the aforementioned phenomena. We will report on our recent measurements of ultracold inelastic molecular collisions as well as our progress towards the trapping of absolute ground state polar molecules.

[1]A. Micheli, G.K. Brennen, and P. Zoller, Nature Physics 2, 341 (2006).
[2]E.R. Hudson et al., Phys. Rev. A 73, 063404 (2006).
[3]D. DeMille, Phys. Rev. Lett. 88, 067901 (2002).
[4]D. DeMille et al., Phys. Rev. Lett. 100, 043202 (2008).
[5]E.R. Hudson et al., Phys. Rev. Lett., accepted (2008).
[6]J.M. Sage et al., Phys. Rev. Lett. 94, 203001 (2005).

Repulsive shield between polar molecules

A. V. Gorshkov[1], P. Rabl[1,2], G. Pupillo[3,4], A. Micheli[3,4], P. Zoller[3,4], M. D. Lukin[1,2], H. P. Büchler[5]

[1]*Physics Department, Harvard University, Cambridge, MA 02138, USA*
[2]*Institute for Theoretical Atomic, Molecular and Optical Physics, Cambridge, MA 02138, USA*
[3]*Institute for Quantum Optics and Quantum Information, 6020 Innsbruck, Austria*
[4]*Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria*
[5]*Theoretische Physik III, University of Stuttgart, 70155 Stuttgart, Germany*

We propose and analyze a technique that allows to suppress inelastic collisions and simultaneously enhance elastic interactions between cold polar molecules. The main idea is to cancel the leading dipole-dipole interaction with a suitable combination of static electric and microwave fields in such a way that the remaining van-der-Waals-type potential forms a three-dimensional repulsive shield. We analyze the elastic and inelastic scattering cross sections relevant for evaporative cooling of polar molecules and discuss the prospect for the creation of crystalline structures.

Magnetic trapping of atomic nitrogen (^{14}N) and cotrapping of NH ($X^3\Sigma^-$)

M. T. Hummon[1,2], W. C. Campbell[1,2], H.-I Lu[2,3], E. Tsikata[1,2], Y. Wang[1,2], J. M. Doyle[1,2]

[1]*Department of Physics, Harvard University, Cambridge, MA 02138*
[2]*Harvard-MIT Center for Ultracold Atoms, Cambridge, MA 02138*
[3]*School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138*

We observe magnetic trapping of atomic nitrogen (^{14}N) and cotrapping of ground state imidogen (^{14}NH, $X^3\Sigma^-$). Both are loaded directly from a room temperature beam via buffer gas cooling. We trap approximately 1×10^{11} ^{14}N atoms at a peak density of 5×10^{11} cm^{-3} at 550 mK. The 12 +5/−3 s $1/e$ lifetime of atomic nitrogen in the trap is consistent with loss via elastic collisions with the helium buffer gas. This results in a limit on the ^{14}N-^{3}He inelastic collision rate coefficient of $k_{\rm in} < 2.2 \times 10^{-16}$ cm^3 s^{-1}. Cotrapping of ^{14}N and ^{14}NH is accomplished, with 10^8 NH trapped molecules at a peak density of 10^8 cm^{-3}.

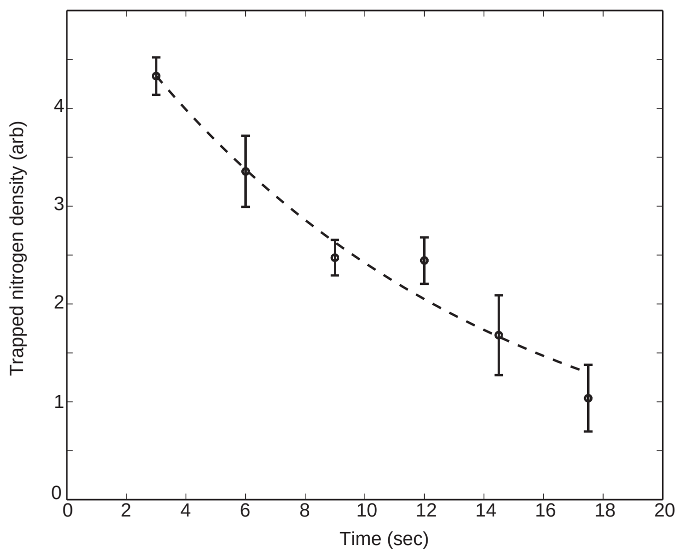

Figure 1: *Trapped nitrogen density vs. time after trap loading. An exponential fit (dashed line) to the data yields a $1/e$ trap lifetime of 12+5/−3 s.*

Photoassociation of ultracold LiCs molecules

J. Deiglmayr[1,2], A. Grochola[1], C. Glück[1], K. Mörtlbauer[1], M. Repp[1], J. Lange[1], S. D. Kraft[1], R. Wester[1], M. Weidemüller[1], M. Aymar[2], O. Dulieu[2]

[1] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Germany*
[2] *Laboratoire Aimé Cotton, Orsay, France*

Ultracold molecular gases find many applications, reaching from high resolution spectroscopy over tests of the standard model to quantum chemistry and quantum computing [1]. Heteronuclear alkali dimers have a permanent dipole moment and therefore exhibit strong anisotropic and long-range electric dipole interactions. This allows precise control of internal and motional degrees of freedom by electric fields, thereby offering intriguing perspectives for the study of strongly-correlated many-body quantum systems. The LiCs molecule is an especially promising candidate for observing these interactions, since it posses the strongest dipole moment of all alkali dimers of up to 5.5 Debye in the ground state [2].
Here we present the photoassociation of ultracold LiCs molecules, stabilized by radiative decay. The molecules are detected using multiphoton ionization spectroscopy with a high-resolution time-of-flight mass spectrometer [3]. Active photoassociation in an overlapped Cesium dark SPOT/Lithium MOT, loaded from a single Zeeman-slower, is found to yield a strongly increased production rate compared to photoassociation by the trapping light of a two species MOT [4]. We identify photoassociation resonances in the $B^1\Pi$ potential up to $300\,\mathrm{cm}^{-1}$ below the $2S_{1/2}$-$6P_{3/2}$ asymptote. This spectroscopic data makes the yet unknown connection from the recently measured inner part of the $B^1\Pi$ state [5] to the molecular asymptote and yields a significantly improved value for the ground state dissociation energy. The perspectives for the production of LiCs molecules in the absolute ground state are evaluated and future experiments with an ultracold gas of polar LiCs molecules are outlined.
In addition we have studied scenarios for the alignment of ultracold dipolar molecules, based on combinations of static electric fields and strong laser fields [6]. For this purpose we calculated the static polarizability tensor for the ground state of all heteronuclear alkalis [7].

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[2] M. Aymar, O.Dulieu, J. Chem. Phys. **122**, 204302 (2005)
[3] SD Kraft *et al.*, Appl. Phys. B **89**, 453 (2007)
[4] SD Kraft *et al.*, J. Phys. B **39**, S993 (2006)
[5] A. Stein *et al.*, to appear in Eur.Phys. J. D, (2008)
[6] B. Friedrich et D. Herschbach, J. Phys. Chem. A 103, 10280 (1999)
[7] J. Deiglmayr *et al.*, submitted to J. Chem. Phys.

Quantum Gas of Deeply Bound Ground State Molecules

J. G. Danzl[1], E. Haller[1], M. Gustavsson[1], M. J. Mark[1], R. Hart[1], N. Bouloufa[2], O. Dulieu[2], H. Ritsch[3], H. C. Nägerl[1]

[1]*Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*
[2]*Laboratoire Aimé Cotton, CNRS, Université Paris-Sud, 91405 Orsay Cedex, France*
[3]*Institut für Theoretische Physik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

Ultracold samples of molecules are ideally suited for fundamental studies in physics and chemistry. For many of the proposed experiments full control over the molecular wave function in specific deeply bound rovibrational states is needed. We create an ultracold dense quantum gas of deeply bound Cs_2 molecules in the $v = 73$ vibrational level of the $X^1\Sigma_g^+$ ground state, bound by more than 1000 wavenumbers or $h \times 30$ THz [1]. Weakly bound molecules are first produced on a Feshbach resonance from a Bose-Einstein condensate of cesium atoms. The molecules are then transferred to the $v = 73$, $J = 2$ level of the X state by coherent optical two-photon transfer using the STIRAP technique. The transfer efficiency exceeds 80%. Coherence of the transfer is demonstrated in a Ramsey-type experiment. We show that the sample is not heated during the transfer, essentially inheriting the high phase space density of the original atomic sample.
We discuss the progress for the implementation of the next step in which we aim to transfer the molecules into the rovibrational ground state $v = 0$, $J = 0$ of the X state. Our results show that the preparation of a quantum gas of molecules in arbitrary rovibrational levels is possible and that the creation of a Bose-Einstein condensate of molecules in the rovibronic ground state is within reach.

[1]Danzl *et al.*, manuscript submitted for publication

Trapping Stark decelerated cold molecules

J. J. Gilijamse, S. Hoekstra, S. Y. T. van de Meerakker, G. Meijer

Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany

With a Stark decelerator, bunches of state-selected molecules with a controlled velocity and with longitudinal temperatures as low as a few mK can be produced. After molecules are decelerated to low enough velocity they can be loaded in a trap, and can be accurately studied exploiting the long interaction times afforded by a trap.

We will present the use of three different types of traps. One is an electrostatic trap that relies on the Stark shift of polar molecules. This trap has been used to trap OH, OD, CO($a^3\Pi$)[1], and NH($a^1\Delta$)[2] in this experiment. The lifetimes of several vibrationally or electronically excited states have been measured with unprecedented accuracy.

A second trap, existing of two magnetic coils, confines molecules using the Zeeman shift. So far it has been successfully used to trap metastable NH. In combination with an electric loading field, this trap can be used for a reloading scheme in which NH molecules are decelerated to a standstill in the metastable $(a^1\Delta)$ state, optically pumped via the $(A^3\Pi)$ excited state to the ground state, and finally magnetically trapped in this $X^3\Sigma^-$ state[3]. We will report the first results of the implementation of this scheme. A cheap and simple alternative to this technically challenging electromagnetic trap is to build a trap out of permanent magnets, as already demonstrated in the group of Jun Ye (JILA). Until now we have used permanent magnets to retro-reflect ground state OH molecules and focus them transversally as well as longitudinally[4].

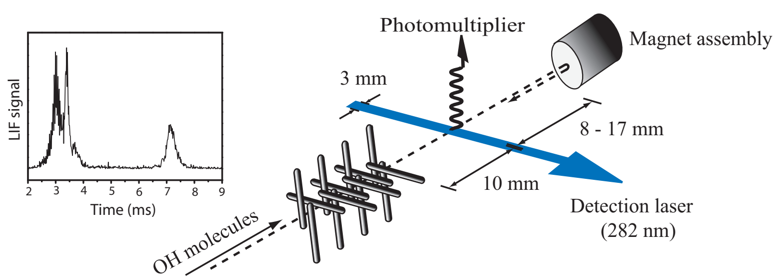

Figure : *The retro-reflection experiment of OH molecules. Only the last 7 (from a total 108) electrode pairs of the decelerator are shown. The graph in the upper left corner shows a time-of-flight profile for a beam of ground-state OH molecules decelerated from 390 m/s to 15 m/s. The undecelerated molecules arrive in the detection zone about 3 ms after their production in the source region, whereas the decelerated ones take some 4 ms longer.*

[1]The radiative lifetime of metastable CO $(a^3\Pi, v = 0)$, J.J. Gilijamse *et. al.*, JCP 127, 221102 (2007)
[2]Electrostatic trapping of metastable NH molecules, S. Hoekstra *et. al.*, PRA 76, 063408 (2007)
[3]Optical pumping of metastable NH radicals into the paramagnetic ground state, S.Y.T van de Meerakker *et. al.*, PRA 68, 032508 (2003)
[4]Reflection of OH molecules from magnetic mirrors, M. Metsälä *et. al.*, NJP, in press (may, 2008)

Progress Towards Forming Ultracold ^{85}Rb$_2$ Molecules in an Optical Dipole Trap

H. K. Pechkis, M. Bellos, R. Carollo, J. Ray Majumder,
E. E. Eyler, P. L. Gould, W. C. Stwalley

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

We report our progress towards the efficient production of ultracold Rb$_2$ molecules in a quasi electrostatic optical trap (QUEST) by photoassociation (PA). The QUEST is loaded from a magneto-optical trap (MOT), with additional cooling and compression stages to optimize the density and temperature. The trapped atom cloud is detected by absorption imaging. Molecules will be formed from the optically trapped atoms by PA to levels bound by $\approx$ 1-100 cm^{-1}, followed by radiative decay. Employing the QUEST will allow optical trapping of Rb$_2$ in the singlet $X\,^1\Sigma_g^+$ state, as well as enhancing greatly the PA rates for forming these ultracold molecules. We observed the enhancement of PA in the optical dipole trap compared to PA in the MOT alone. Trapped molecules in the dipole trap will be detected by resonant-enhanced multi-photon ionization (REMPI). We will present in more detail our progress in experimentally forming ultracold molecules in the dipole trap and progress toward experiments on collisions involving the trapped molecules. This work is supported by the National Science Foundation.

Weakly-bound molecules. Analysis by the Lu-Fano method coupled to the LeRoy-Bernstein model.

H. Jelassi[1,2], B. Viaris de Lesegno[2], L. Pruvost[1] [1]

[1] *Laboratoire Aimé Cotton, CNRS, bat 505, univ Paris-Sud, 91405 0rsay cedex, France*
[2] *Laboratoire Collisions, Agrgats, Ractivit, UMR 5589, IRSAMC, Université P. Sabatier, 118 Route de Narbonne, 31062 Toulouse cedex France*

We have performed experiments on the photo-associative spectroscopy of cold ^{87}Rb atoms, below the 5s$_{1/2}$-5p$_{1/2}$ dissociation limit, producing weakly-bound excited molecules. With the trap loss spectroscopy technique we have recorded spectra, which exhibit the the 0_g^-, 0_u^+ and 1_g molecular vibrational series. The measured energies of the molecular levels allow us to determine properties of the molecular potentials.
Such weakly-bound molecules are described by the dipole-dipole atom interaction which varies, according to the molecular symmetry, either as $1/R^3$ or as $1/R^6$, where R is the inter-nuclear distance. The eigen energies of the weakly-bound molecules are then very close to those obtained by the well-known LeRoy-Bernstein model. The discrepancies to the LeRoy-Bernstein law are due to the short distance behavior of the molecular potential or to couplings to other molecular potentials due to interactions, for example spin-orbit or spin-spin interactions. The analysis of the discrepancies reveals these interactions.
To analyze the data, we have adapted the Lu-Fano method - extensively applied to Rydberg atoms in the past - to the weakly-bound molecules. Using the LeRoy-Bernstein law, a *molecular vibrational quantum defect* is defined and derived from the data. Its variation versus the binding energy gives the Lu-Fano graph which allows us to characterize the molecular potential and the interactions.
From the experimental data of te 0_g^- state, we obtain a Lu-Fano graph with a linear shape which is the signature of the short range behavior of the molecular potential [2]. A model for the barrier allows us to connect the slope to its location. The method has also been applied to 0_g^- levels of ^{85}Rb and ^{133}Cs [3].
The Lu-Fano graph of the 0_u^+ molecular levels exhibits sharp variations, signature of a coupling with a neighboring molecular series. The coupling is due to the spin-orbit and spin-spin interactions in the molecule [4]. A two series model allows us to evaluate the coupling, to identify two perturbing levels of the 5s$_{1/2}$-5p$_{3/2}$ 0_u^+ series. A strong wave function mixing is deduced suggesting an efficient scheme for cold molecule formation. We also predict the energy position and the width of its first pre-dissociated level, which was confirmed by an experimental signal. The method has also been successfully applied to data of Cs_2 [5].

[1] laurence.pruvost@lac.u-psud.fr
[2] H. Jelassi, B. Viaris De Lesegno, L. Pruvost, Phys. Rev. A. 73, 32501, 2006
[3] H. Jelassi, B. Viaris De Lesegno, L. Pruvost, AIP Conference Proceedings ; ISC 2007 935 p. 203, 2007
[4] H. Jelassi, B. Viaris De Lesegno, L. Pruvost, Phys. Rev. A. 74, 12510, 2006
[5] H. Jelassi, B. Viaris De Lesegno, L. Pruvost, M. Pichler, W. Stwalley, submitted to Phys. Rev. A

Lifetime of exotic dimers of ultracold metastable helium

M. Leduc[1], M. Portier[1], S. Moal[1], N. Zahzam[1,2]

[1] *Laboratoire Kastler Brossel, Ecole Normale Supérieure, CNRS, Université Pierre et Marie Curie, 24 rue Lhomond 75231 Paris Cedex*
[2] *Office National d'études et de recherche aérospatiales, Chemin de la Hunière, 91761 Palaiseau Cedex*

We shall present results of two-photon photoassociation experiments dealing with a gas of helium atoms in the 2^3S_1 metastable state taken to a temperature range of 2 to 10 μK by evaporative cooling in a magnetic trap (see Figure 1). Atom-molecule dark resonance signals, as well as Raman signals provide information on the exotic molecules in the least bound state ($J = 2,\ v = 14$) of the interaction potential between two spin-polarized metastable atoms. The intrinsic lifetime of this dimer is derived from measuring the line width of the signals[1], after eliminating the contribution of the thermal broadening. We interprete the molecule lifetime in terms of ionization process. As the two metastable atoms are spin polarized when they collide and form the molecule, Penning ionization is inhibited by the electronic polarization, unless spin relaxation takes place, resulting from the weak spin dipole coupling between the quintet ${}^5\Sigma_g^+$ and the singlet ${}^1\Sigma_g^+$ states. We shall present a theoretical calculation of the molecular lifetime [2] and compare it with a previous estimate [3]. We shall discuss the discrepancy between these theoretical values and our experimental measurement. The possible influence of atom-molecule inelastic collisions will also be discussed.

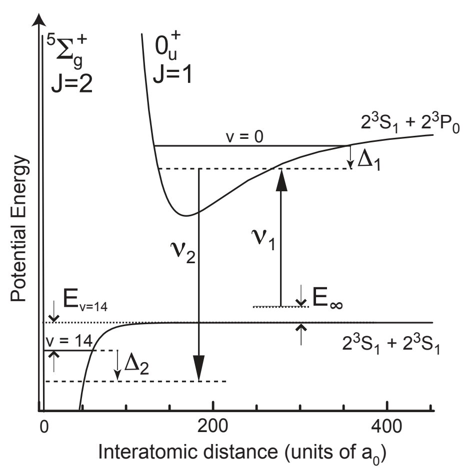

Figure 1: *Two-photon photoassociation of spin-polarized metastable helium.*

[1] S. Moal et. al, Phys. Rev. A, **75**, 033415 (2007)
[2] M. Portier, PhD thesis, available at http://tel.archives-ouvertes.fr/tel-00258383
[3] T. Beams et al., Phys. Rev. A, **74** 014702 (2006)

Formation of deeply bound molecules via chainwise adiabatic passage

Elena Kuznetsova[1,2], P. Pellegrini[1], R. Côté[1], M. D. Lukin[2,3], S. F. Yelin[1,2]

[1] *Department of Physics, Uiversity of Connecticut, Storrs, CT 06269, USA*
[2] *ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[3] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*

Ultracold molecular gases open possibilities for studyng new exciting physical phenomena and their applications, such as testing fundamental symmetries, precision spectroscopy, ultracold chemistry, simulation of condensed matter systems and quantum computing. Dense samples of ultracold molecules in their ground rovibrational state $v = 0, J = 0$ are required for many of these applications. Currently translationally ultracold (100 nK - 1 mK) molecules are produced by magneto- and photoassociation techniques. These molecules, however, are vibrationally hot, being formed in high vibrational states near the dissociation limit of the electronic ground state. Therefore, once created, molecules have to be rapidly transfered to the ground rovibrational state.
We suggest and analyze a novel technique for efficient and robust creation of dense ultracold molecular ensembles in their ground rovibrational state. In our approach a molecule is brought to the ground state through a series of intermediate vibrational states via a multistate chainwise Stimulated Raman Adiabatic Passage (c-STIRAP) technique. We study the influence of the intermediate states decay on the transfer process and suggest an approach that minimizes the population of these states, resulting in a maximal transfer efficiency. We apply the technique to bosonic, fermionic and mixed alkali dimers, taking into account major decay mechanisms due to vibrationally inelastic atom-molecule and molecule-molecule collisions. As an example, we analyze the formation of $^{87}Rb_2$ starting from an initial Feshbach molecular state. Numerical analysis suggests a transfer efficiency $> 90\%$, even in the presence of strong collisional relaxation as are present in a high density atomic gas.

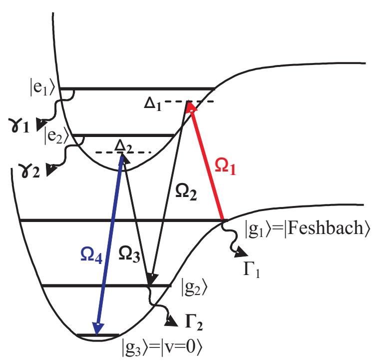

Figure 1: *Schematic showing the multistate chainwise STIRAP transfer from the Feshbach state $|g_1\rangle$ to the ground $|g_3\rangle = |v = 0\rangle$ state*

Cold Rydberg atom pair excitation in the presence of AC/DC electric fields

V. A. Nascimento[1], J. S. Cabral[1], L. L. Carili[1], A. Schwettmann2[2], J. P. Shaffer[2], L. G. Marcassa[1]

[1]*Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brazil*
[2]*University of Oklahoma, Norman, USA*

We present experimental results that show a significant yield of nP atoms after excitation of nS Rb Rydberg atoms from a MOT using a pulsed dye laser, where $29 < n < 37$. The observed nP population is quadratically dependent on the nS atomic density. Such results are naturally attributed to binary collisions. However, this cannot be the case here, because the interaction between Rb nS atoms is repulsive. In this experiment, the AC Stark effect, dipole dipole interactions, and DC Stark effect work together to create a nonvanishing final population of $nP(n-1)P$ pairs. The background electric field and multipole interactions cause an admixture of $nS-nS$ character into the $nP(n-1)P$ pairs. The AC Stark shift from the laser pulse shifts the intermediate state into resonance with the $nP(n-1)P$ final pair. We compare our results to calculations done by numerically solving the density matrix equations for a two-photon excitation of the $nP(n-1)P$ pair state at $0.55 < R < 1.8\ \mu$. This leads to an estimated $32P$ to $32S$ signal ratio of 3.9 %, which is in excellent agreement with the experimental value of 2.6 %. The principal quantum number dependence of $nP/(nS)^2$ population was also measured, and it was shown to be consistent with our model. During the presentation, we will also discuss the DC electric field dependence. We believe that the control of electric field effects with regard to Rydberg atom interactions is important in order to use these novel and interesting systems for dipole blockade and quantum computation.

Rovibrational Dynamics and Photoassociation of Cold Heteronuclear Dimers in Electric Fields

M. Mayle[1], R. González-Férez[2], P. Schmelcher[1,3]

[1] *Theoretische Chemie, Physikalisch–Chemisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany*
[2] *Instituto 'Carlos I' de Física Teórica y Computacional and Departamento de Física Atómica Molecular y Nuclear, Universidad de Granada, E-18071 Granada, Spain*
[3] *Physikalisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany*

A comparative study of the effect of a static homogeneous electric field on the rovibrational spectra of several polar dimers in their $X^1\Sigma^+$ electronic ground state is performed. Focusing upon the rotational ground state within each vibrational band, results for energies and various expectation values are presented. For moderate field strengths the electric field-induced energy shifts, orientation, alignment, and angular motion hybridization are analyzed up to high vibrational excitations close to the dissociation threshold [1].
Furthermore, the formation of ultracold molecules via stimulated emission followed by a radiative deexcitation cascade in the presence of a static electric field is investigated. By analyzing the corresponding cross sections, the possibility to populate the lowest rotational excitations via photoassociation is demonstrated [2]. The modification of the radiative cascade due to the electric field leads to narrow rotational state distributions in the vibrational ground state [3].

[1] R. González-Férez, M. Mayle, P. Sánchez-Moreno and P. Schmelcher, to be published
[2] R. González-Férez, M. Weidemüller and P. Schmelcher, "Photoassociation of Cold Heteronuclear Dimers in Static Electric Fields", Phys. Rev. A **76**, 023402 (2007)
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Stark deceleration of cold lithium hydride molecules

S. K. Tokunaga, J. O. Stack, I. S. Bhatti, J. J. Hudson, B. E. Sauer, E. A. Hinds, M. R. Tarbutt

Centre for Cold Matter, Blackett Laboratory, Imperial College London, London SW7 2BW, United Kingdom

We present recent results on the Stark deceleration[1] of cold lithium hydride molecules to low velocity. We produce pulsed beams of LiH, with a translational temperature of 1 K, by laser ablation of lithium into a supersonically expanding carrier gas containing hydrogen[2]. Most of the molecules are formed in the strong-field seeking rotational ground state which is unsuitable for slowing in the Stark decelerator. We therefore prepare the molecules in the weak-field seeking component of the first rotationally excited state by driving the rotational transition with narrowband radiation at 444 GHz. The molecules then enter a 100-stage Stark decelerator where switched electric field gradients are used to slow them down. Finally, the molecules are detected by laser induced fluorescence at 367 nm. In the electric field of the decelerator, the Stark shift of LiH is far from linear, unlike many of the molecules that have been decelerated previously. Using this apparatus, we have reduced the velocity of the molecules from an initial 420m/s down to a trappable 53m/s, corresponding to a 98.5% reduction in kinetic energy.

The work we present is one component of a project to produce ultracold molecules by sympathetic cooling with ultracold atoms. We plan to trap cold LiH together with ultracold Li. Elastic atom-molecule collisions will cool the molecules, while inelastic collisions will tend to lead to trap loss. It is likely that the ratio of elastic to inelastic processes will be highly unfavourable unless the inelastic processes are energetically forbidden[3,4]. Thus, both atoms and molecules should be trapped in their lowest-lying states. We consider some possible trapping geometries.

[1] H. L. Bethlem, G. Berden and G. Meijer, Phys. Rev. Lett. **83**, 1558 (1999)

[2] S. K. Tokunaga, J. O. Stack, J. J. Hudson, B. E. Sauer, E. A. Hinds and M. R. Tarbutt, J. Chem. Phys. **126**, 124314 (2007)

[3] M. Lara, J. L. Bohn, D. Potter, P. Soldán and J. M. Hutson, Phys. Rev. Lett., **97**, 183201 (2006)

[4] P. S. Zuchowski and J. M. Hutson, arXiv:0805.1705v1 (2008)

Dynamics of polar molecules in alternating gradient guides and decelerators

T. E. Wall, S. Armitage, J. F. Kanem, J. J. Hudson B. E. Sauer, E. A. Hinds, M. R. Tarbutt

Centre for Cold Matter, Blackett Laboratory, Imperial College London, London SW7 2BW, United Kingdom

Neutral particles can be guided using electric field gradients that focus in one transverse direction and defocus in the other, alternating between the two directions. Such a guide is suitable for focussing and decelerating polar molecules that are attracted to strong electric fields, which unlike their weak-field seeking counterparts cannot be confined using static fields[1]. Nonlinear forces are always present in these guides and can severely reduce the phase space acceptance. Using approximate analytical techniques, along with numerical methods, we calculate the influence of the most important nonlinear forces, and show how to choose the guide parameters so that the acceptance is maximized[2].
We have built a 1 m long alternating gradient guide with a four-rod geometry, and a 21-stage alternating gradient Stark decelerator with a two-rod geometry. These we have used to guide and decelerate YbF and CaF molecules. We present our experimental results on guiding and deceleration, and explain the results using some simple models as well as detailed numerical simulations.

[1]H.L. Bethlem, M.R. Tarbutt, J. Küpper, D. Carty, K. Wohlfart, E.A. Hinds and G. Meijer, J. Phys. B. **39**, R263 (2006)

[2]M. R. Tarbutt and E.A. Hinds, arXiv:0804.2077v1

A Near Quantum Degenerate Gas of Triplet $v = 0$ Polar Molecules

K.-K. Ni[1,], S. Ospelkaus[1], M. Miranda[1], A. Pe'er[1], B. Neyenhuis[1], J. J. Zirbel[1], D. Wang[1], S. Kotochigova[2], P. S. Julienne[3], J. Ye[1], D. S. Jin[1]

[1] *JILA, NIST and University of Colorado, Boulder, CO 80309, USA*
[2] *Department of Physics, Temple University, Philadelphia, PA 19122, USA*
[3] *JQI, NIST and University of Maryland, Gaithersburg, MD 20899, USA*

We report on the creation of an ultracold dense gas of polar molecules from an ultracold mixture of Rb and K. Using a single step of STIRAP (STImulate Raman Adiabatic Passage), we demonstrated efficient state transfer from weakly-bound Feshbach molecules to the triplet rovibrational ground state. The triplet ground molecular gas has a density of 10^{12} cm^{-3} with quantum degeneracy $T/T_F = 3$. The ground-state molecules exhibit an permanent electric dipole moment. We will report our recent measurement of the permanent electric dipole moment. We will also present our progress toward state transfer to the singlet rovibrational ground state.

A Simple Model for Feshbach Molecule Bound States

P. S. Julienne[1], E. Tiesinga[1], C. Chin[2]

[1] *Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, 100 Bureau Drive, Gaithersburg, Maryland 20899-8423, USA*
[2] *Department of Physics and James Franck Institute, University of Chicago, Chicago, Illinois 60637, USA*

A Feshbach resonance and its associated bound state play an essential role in many experiments with ultracold atomic gases and lattices. We present simple models for such a bound state that applies beyond the limit of universality. The scale length $\bar{a}$ associated with the long-range van der Waals potential[1] provides key length and energy scales for classifying resonance properties[2]. A model of interacting closed and open channels, represented by square wells of width $\bar{a}$, gives a simple coupled equation similar to that of multichannel quantum defect theory for finding the energy of the near threshold bound state. The closed channel fraction Z in the eigenstate is readily found from the solution. The "box" model gives good agreement with full coupled channels calculations of the binding energy and Z for a wide range of resonances spanning many orders of magnitude in width and can be extended to overlapping resonances.

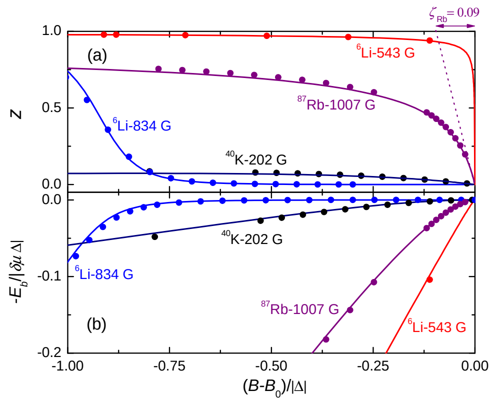

Figure 1: *Energy (b) and closed channel fraction Z (a) of selected Feshbach resonances, labeled by species and resonance position B_0. Lines are from a "box" model, and points are from full coupled channels calculations. Detuning of magnetic field B from B_0 is given in units of the resonance width Δ and binding energy E_b in units of $\delta\mu\Delta$, where $\delta\mu$ is the magnetic moment difference between the separated atoms and the "bare" closed channel molecular bound state.*

[1] G. F. Gribakin and V. V.Flambaum, Phys, Rev. A 48, 546 (1993)
[2] T. Köhler, K. Goral, and P. S. Jullienne, Rev. Mod. Phys. 78, 1311 (2006)

Giant formation rates of ultracold molecules via Feshbach Optimized Photoassociation

P. Pellegrini, M. Gacesa, R. Côté

Department of Physics, University of Connecticut, Storrs, CT 06269, USA

Ultracold molecules have attracted a lot of attention due to their broad potential applications in metrology, high precision spectroscopy or quantum computing. The ability to form and control ultracold molecules has drastically improved over the last decade but producing stable molecules in their lowest vibrational levels still remains challenging. We present a theoretical investigation of the photoassociation of atoms in the vicinity of a Feshbach resonance for the production of ultracold stable molecules. Full molecular quantum coupled-channel calculations showed that large molecular formation rates can be obtained, with enhancement of several orders of magnitude over off-resonance cases. We illustrate this effect with both homonuclear and heteronuclear dimers. We will also present a simple analytical model for the photoassociation rates.

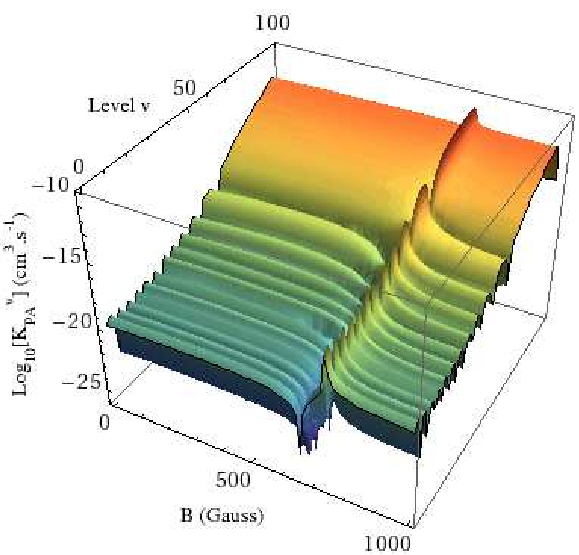

Figure 1: *Photoassociaitonn rates to the excited vibrational levels v of the* $1^3\Sigma_g^+(2s+2p)$ *of* $^7Li_2$ *as function of the magnetic field B showing the enhancement as we cross the Feshbach resonance at 735G.*

Observation of a Shape Resonance in Cold Ground State Rb_2 Molecule Formation

C. R. Menegatti, B. S. Marangoni, L. G. Marcassa

Instituto de Física de São Carlos, University of São Paulo, São Carlos, Brazil

About a decade ago, cold ground state Rb_2 molecules were detected for the first time in magneto-optical traps[1]. The formation of such molecules is due to photoassociation process by the trapping laser beam, which is by itself very surprising. In the last years, several experiments were devoted to trap such cold molecules, promoting a great deal of possibilities in the investigation of cold molecule collisions. However, the molecule formation due to photoassociation by the trapping laser still presents several open questions. In this work, we investigate the molecule formation rate as a function of the atomic sample temperature. Briefly, there are three phases in the experiment: i) trapping; ii) molasses; and iii) probe phase. First, using a standard MOT the ^{85}Rb atoms are trapped. Then for 4 ms, a molasses phase is applied, and the atoms are cooled. The final temperature of the atomic sample is determined by time of flight technique. In the probe phase, the atoms are illuminated by the trapping laser beam to form the cold molecule. And in the sequence, a pulsed dye laser (1 mJ/pulse, 4 ns, λ = 603 nm) photoionizes the cold molecules. The ions are collected by a channeltron and analyzed by a boxcar integrator gate. By time of flight the atomic ions can be discriminated from the molecular ions. The number of trapped atoms is determined by fluorescence. All these parameters allow us to measure the cold ground state Rb_2 molecule formation rate as a function of the atomic temperature (fig.1). We observed a peak around 130 μK, which is consistent with the existence of a partial wave resonance[2]. We have also measured the molecular temperature as a function of the atomic sample temperature. Our results indicate that more theoretical work is necessary in order to understand the photoassociation process due to the trapping laser beam. This work has received financial support from Fapesp and CNPq - Brazilian Agencies.

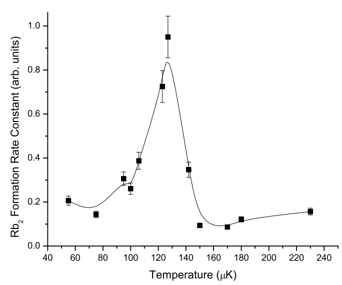

Figure 1: *Cold ground state Rb_2 molecule formation rate as a function of the atomic temperature.*

[1] A. Fioretti et al., Phys. Rev. Lett. 80, 4402 (1998); C. Gabanini et al, Phys. Rev. Lett. 84, 2814 (2000).
[2] H. Boesten et al., Phys. Rev. Lett. 77, 5194 (1996).

Low-Temperature Collisions Utilizing Trapped OH

B. C. Sawyer, B. K. Stuhl, D. Wang, M. Yeo, J. Ye

JILA, National Institute of Standards and Technology and University of Colorado Department of Physics, University of Colorado, Boulder, CO 80309-0440, USA

Advances in cold molecules promise to profoundly impact research on precision measurement, quantum information, and controlled chemistry. We employ a Stark decelerator to slow a supersonic beam of ground-state OH molecules from 500 m/s to 36 m/s. We subsequently trap a 70 mK sample of the decelerated molecules at a density of 10^6 cm^{-3} within a magnetoelectrostatic trap (MET) whose center lies 1 cm from the decelerator exit. We have improved upon our previous MET design[1] by replacing the high-current coils with permanent ring magnets and reducing the trap dimensions to better match the molecular packet. A large electric field is applied to the nickel coatings of the permanent magnets to stop the OH packet within the magnetic quadrupole. We report progress toward observation of collisions between trapped OH and a tunable atomic beam of He with an energy resolution of 9 cm^{-1}. The velocity of the colliding He beam is adjusted by varying the nozzle temperature of the pulsed valve, thereby tuning the OH-He center-of-mass collision energy from $\sim$ 60–250 cm^{-1}. Inelastic cross sections for transitions to excited spin-orbit and rotational levels can be probed over this energy range. In addition to being completely open in the radial dimension, our trap design allows for the application of a polarizing electric field to the trapped sample to facilitate future polar-molecule collision studies.

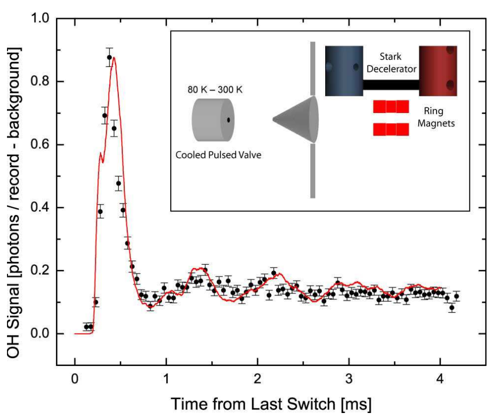

Figure 1: *Time-of-flight data displaying OH molecules as they are stopped and trapped within the MET. The solid line is the result of Monte Carlo simulation. The large initial peak at 400 μs is the stopped OH packet, while the trapped molecules undergo oscillations beyond $\sim$1 ms. The inset is an illustration of the MET and decelerator along with the pulsed valve and skimmer used for collision studies.*

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Nearly degenerate levels in Cs_2 with amplified sensitivity to variation of $\mu = m_e/m_p$

D. DeMille[1], S. K. Sainis[1], J. Sage[1], T. Bergeman[2], S. Kotochigova[3], E. Tiesinga[4]

[1]*Department of Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Department of Physics and Astronomy, SUNY, Stony Brook, New York 11794, USA*
[3] *Physics Department, Temple University, Philadelphia, Pennsylvania 19122, USA*
[4]*Joint Quantum Institute and Atomic Physics Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*

Astrophysical searches currently yield stringent bounds at the level $10^{-15}/year$ on the time variation of μ [1]. From the perspective of laboratory searches for time-variation of μ, the differing sensitivity of molecular vibrational levels to variations in μ offers an interesting possibility. For a diatomic molecule in a strongly-bound vibrational state ν, the sensitivity of the vibrational energy E_ν to a fractional change in μ is given by $\partial_\mu E_\nu = E_\nu/2$. Thus a high-lying vibrational state can have much greater sensitivity to changes in μ than a low-lying vibrational level. A transition between a pair of nearly-degenerate vibronic levels one from a deep electronic state, the other from a shallow electronic state– possesses both a high relative and a high absolute sensitivity to the time-variation of μ. The ground state manifold of Cs_2 consisting of the overlapping deep $X^1\Sigma_g^+$ and shallow $a^3\Sigma_u^+$ electronic potentials is an attractive candidate for implementing such a scheme.

We present spectroscopic evidence verifying the presence of a near degeneracy in the ground vibronic levels of Cs_2. Starting with spin-polarized ultracold ($T = 100\mu K$) Cs atoms ($F = 4, m_F = 4$), we use a two-color photoassociation process via the $(2)0_g^-$ excited state to observe the rich hyperfine and rotational sub-structure in deeply-bound vibrational levels of the $a^3\Sigma_u^+$ ground state of Cs_2. The observed line strengths and positions agree with predictions for the long-range part of the $a^3\Sigma_u^+$ state. We report the presence of an unexpected line in the $\nu_a = 37$ vibration level. We attribute this line to hyperfine and second-order spin-orbit mixing of nearly-degenerate singlet and triplet levels in the ground-state manifold. The fits to our data can accurately predict the position of other nearby, unobserved $X^1\Sigma_g^+$ state sublevels ideal for use in the proposed experiment.

Based our spectroscopic data, we calculate the amplified relative and absolute sensitivity of a transition between such pairs of nearly degenerate vibrational levels of the $X^1\Sigma_g^+$ and $a^3\Sigma_u^+$ electronic potentials. Recent advances in the production of ultracold Cs_2 molecules should make it possible to carry out narrow linewidth spectroscopy of such nearly degenerate levels [2]. We propose experiments that would make it possible to detect to changes in μ at the level 10^{-17}/year or better [3].

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[2]C. Chin et al., Phys. Rev. Lett. 90, 033201 (2003); M. Mark et al., Europhys. Lett. 69, 706 (2005).

[3]DeMille et al. Phys. Rev. Lett. 100, 043202 (2008).

Many-body effects in the production of Feshbach molecules

T. M. Hanna[1], T. Köhler[2]

[1]*Atomic Physics Division, National Institute of Standards and Technology, 100 Bureau Drive Stop 8423, Gaithersburg MD 20899-8423, USA.*
[2]*Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK.*

We have derived and implemented a non-Markovian Boltzmann-like equation for the dynamics of an ultracold thermal Bose gas. Our approach includes time-varying two-body interactions and accounts for rethermalisation effects in the atomic gas. The Boltzmann equation is recovered in the limit of long times and stationary interactions. We calculate the dynamics of the one-body density matrix, which can then be used to calculate quantities such as the production efficiency of Feshbach molecules. For the case of low molecule production efficiency, with a correspondingly small depletion of the atomic gas, our approach recovers the limit in which the efficiency is given by a weighted average over the two-body transition probability density. By considering higher depletions we see the onset of many-body effects, which reduce the predicted efficiency from the small-depletion limit. The nonlinearity of our equations leads to a saturation of the predicted molecule production efficiency, and allows us to examine a range of dynamical effects in ultracold gases.

Magnetic Trapping and Zeeman Relaxation of NH Molecules

E. Tsikata, W. C. Campbell, H.-I Lu, Laurens van Buuren, J. M. Doyle

Department of Physics, Harvard University, Cambridge, MA 02138, USA

NH molecular radicals are magnetically trapped in the presence of a helium buffer gas and their Zeeman relaxation and energy transport collisional cross-sections with helium are measured. Molecules are loaded from a molecular beam into a cold buffer gas cell in a 4T anti-Helmholtz magnetic trap. The NH-He energy transport cross-section is measured to be $2.7\pm 0.8\times10^{-14}\mathrm{cm}^2$ at 710 mK. The inelastic (Zeeman state changing) cross-section is also measured to be $3.8 \pm 1.1\times10^{-19}\mathrm{cm}^2$ at 710 mK, indicating a γ (elastic to inelastic cross-section ratio) of 7×10^4, in agreement with the theory of Krems et al (PRA 68 051401(R) (2003)). Cross-section measurements are obtained for the interaction of the molecular isotopes ^{14}NH, ^{14}ND, ^{15}NH and ^{15}ND with the helium isotopes He-3 and He-4.

Ultracold Molecules for Precision Measurements

T. Zelevinsky[1,2], S. Kotochigova[3], J. Ye[2]

[1]*Department of Physics, Columbia University, New York, NY 10027-5235, USA*
[2]*JILA, NIST and University of Colorado, Boulder, CO 80309-0440, USA*
[3]*Department of Physics, Temple University, Philadelphia, PA 19122-6082, USA*

Optical lattice clocks based on ultracold neutral two-electron atoms were recently successful in achieving systematic uncertainties[1] near 1×10^{-16} and absolute uncertainties[2] below 10^{-15}, and in placing new limits on the gravitational coupling of fundamental constants[3]. This has demonstrated the place of two-electron alkaline earth atoms in the world of precision measurements. We have investigated the possibility of producing ultracold homonuclear molecules based on two-electron atoms such as ^{88}Sr, and using them in precision measurements. Such a molecular system would benefit from the ultracold temperatures and optical-lattice tight trapping techniques, while offering opportunities for precision measurements complementary to those available with atomic systems or astronomical observations. Particularly, homonuclear molecules present a model-independent system for tests of time variations of the proton-electron mass ratio. Creation and manipulation of dimers based on ultracold bosonic two-electron atoms is attractive due to the inherent simplicity of their zero-spin ground state molecular potentials[4,5]. The lack of hyperfine or magnetic structure removes many sources of loss, and combined with the existence of laser-accessible metastable molecular potentials allows optical transitions with branching losses of only $\sim 50\%$, on par with many atomic transitions. Further, the systematic sensitivity to stray magnetic fields is greatly reduced. We have determined that the molecules can be transferred from the weakly bound vibrational states to the absolute ground vibrational state in only two optical Raman steps, with low losses. Moreover, we showed that it should be possible to apply the Stark-cancellation optical lattice scheme to vibrational molecular transitions, enhancing the possibilities for precise and accurate spectroscopic measurements.

[1]A. D. Ludlow, T. Zelevinsky, G. K. Campbell, S. Blatt, M. M. Boyd, M. H. G. de Miranda, M. J. Martin, J. W. Thomsen, S. M. Foreman, Jun Ye, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, Y. Le Coq, Z. W. Barber, N. Poli, N. D. Lemke, K. M. Beck and C. W. Oates, "Sr Lattice Clock at 1×10^{-16} Fractional Uncertainty by Remote Optical Evaluation with a Ca Clock", *Science* 319, 1805 (2008).

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[3]S. Blatt, A. D. Ludlow, G. K. Campbell, J. W. Thomsen, T. Zelevinsky, M. M. Boyd, J. Ye, X. Baillard, M. Fouché, R. Le Targat, A. Brusch, P. Lemonde, M. Takamoto, F.-L. Hong, H. Katori and V. V. Flambaum, "New Limits on Coupling of Fundamental Constants to Gravity Using ^{87}Sr Optical Lattice Clocks", *Phys. Rev. Lett.* 100, 140801 (2008).

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Laser-Induced Fluorescence of Metastable He_2 Molecules in Superfluid Helium

W. G. Rellergert, S. B. Cahn, A. Curioni, J. A. Nikkel, J. I. Malinak, J. D. Wright, D. N. McKinsey

Department of Physics, Yale University, New Haven, CT 06520, USA

Ionizing radiation events in superfluid helium result in the copious production of meta-stable He_2 molecules which have a 13 s radiative lifetime in the liquid.[1] We present results on detecting and imaging the molecules by driving them through many fluorescence-emitting transitions during their lifetime.

Figure 1 shows the lowest-lying electronic states and two relevant vibrational levels of the triplet molecules, as well as one cycling transition used to detect them. A single laser pulse at 905 nm can excite a molecule in the $a^3\Sigma_u^+$ state to the $d^3\Sigma_u^+$ state, where it will most often decay to the $b^3\Pi_g$ state emitting a detectable red photon at 640 nm. The $b^3\Pi_g$ state is then rapidly quenched back to the $a^3\Sigma_u^+$ state, and the cycle can be repeated.

We have confirmed that complications due to decays to the long-lived, excited vibrational levels of the $a^3\Sigma_u^+$ state, which would drastically reduce the number of times a molecule can be cycled, can be mitigated with the use of repumping lasers. For instance, a molecule which decays to the $a^3\Sigma_u^+(v = 1)$ state, can be driven to $c^3\Sigma_g^+(v = 0)$ state with a laser at 1073 nm where it will most often decay back to the $a^3\Sigma_u^+(v = 0)$ state. Similarly, a laser at 1099 nm can be used to regain molecules which decay to the $a^3\Sigma_u^+(v = 2)$ state.

This technique gives rise to a new method for detecting ionization events in superfluid helium with applications in the detection of gamma rays, ultracold neutrons, and WIMP dark matter. It also promises to be a powerful tool for visualizing turbulence in superfluid helium.

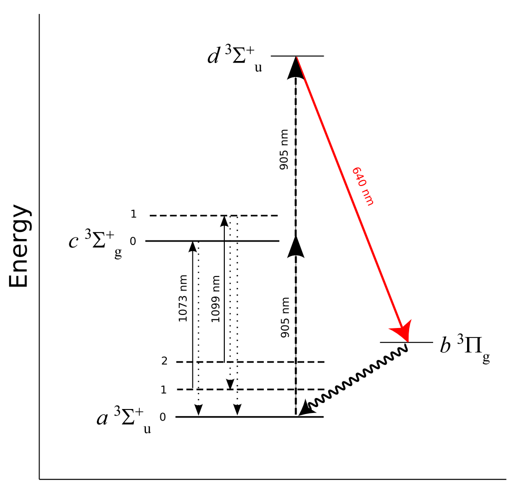

Figure 1: *Energy level diagram of the lowest lying triplet states of the He_2 molecule. The arrows indicate a cycling transition used to detect and image the molecules, as well as transitions used to repump molecules that decay to excited vibrational levels.*

[1] D. N. McKinsey *et al.*, Phys. Rev. A **59**, 200 (1999).

Barium Ion Trap Cavity QED

A. V. Steele, L. R. Churchill, M. Chapman

Physics Dept. Georgia Tech, Atlanta, GA, USA

We propose to use barium ions for studies of cavity quantum electrodynamics and quantum information. Barium has several properties which make it ideal for this purpose. Its states allow for the possibility of implementing either an optical qubit or hyperfine qubit. Additionally, unlike other ions, barium has its primary lines in the visible rather than in the UV. Cavity mirror technology is sufficiently advanced at these wavelengths to allow for the creation of high-finesse optical cavities. Cavities of this type are essential for creating the kind of fast, coherent interaction between internal ion states and cavity photons which will be pursued. The successful integration of ion trap and cavity QED technologies has exciting possibilities for the advancement of quantum information and quantum computation science. The experiment under construction will accomplish this integration by combining a miniaturized linear ion trap with a high-finesse optical cavity.

The effect of ion beam distribution temperature on lateral spread of implanted ions on a solid target

A. M. Ghalambor Dezfuli[1], R. B. Moore[2], E. Ahmadi[3]

[1]*Physics Department, Shahid Chamran University, Ahwaz- Iran*
[2]*Physics Department, McGill University, Montreal-Canada*
[3]*Physics Department, Iran University of science and technology, Tehran-Iran*

Over the years the dimensions of electronics components have been reduced systematically by a factor of two every six years, as formulated in Moors law. However, continued miniaturizations, such as development of nano devices, have been hampered by several outstanding experimental difficulties associated with, in particular lateral spread of implanted materials. This is due principally to the statistical nature of ion-target collisions as well as natural distribution of ion implanted beam. For XLSI circuits lateral straggling is becoming more and more important. In this paper, we present the relationship between the initial temperature of extracted ions from a RF trap and the lateral spread of implanted ions on the solid surface. Ions extracted at different temperature from the trap are modeled based on action diagram method. These ions, after passing through an accelerator system, then interact with a thin layer of silicon. The results show the profound effect of ion temperature on the lateral spread of implanted ions on the surface. Also it shows the lateral spread could be controlled via temperature control of ion implanted distribution.

Temperature control of ion beam surface interaction using rf ion trap

A. M. Ghalambor Dezfuli[1], R. B. Moore[2], E. Ahmadi[3]

[1]*Physics Department, Shahid Chamran University, Ahwaz- Iran*
[2]*Physics Department, McGill University, Montreal-Canada*
[3]*Physics Department, Iran University of science and technology, Tehran-Iran*

As we have showed in our first paper, controlling over temperatures of ion implanting beams has a profound effect on ion implanted distributed materials in ion-surface interaction and thereby changing the futures of nano electronics. In this paper we present a novel system in ion implantation for design and fabrications of nano materials. In this system ion beams from an ion implantation set-up will be trapped in an ion RF trap, cooled with buffer gas and then reaccelerated to desire energies. In such systems, because of the control over temperature of ions, NanoIonBeams with very narrow distributions can be obtained. Such systems will be modelled in this paper. Ion beams, with energy and emittances comparable from an Ion implantation system decelerated and trapped in an Ion RF trap and cooled with buffer gas, are simulated at different temperatures. The results of the simulation will be compared with experimental data. A good agreement between the experimental data and simulations will suggest the future set-up for ion-surface interaction systems.

Segmented Ion Traps for Quantum Computing

D. T. C. Allcock, M. J. Curtis, G. Imreh, A. H Myerson, D. J. Szwer, S. C. Webster, J. A. Sherman, D. N. Stacey, D. M. Lucas, A. M. Steane

Centre for Quantum Computation, Clarendon Laboratory, Oxford University, UK

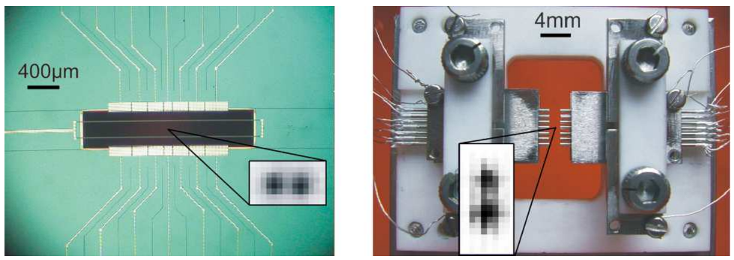

Figure 1: *The two traps with two Ca^+ ions loaded in each (insets).*

We report the successful loading of $^{40}Ca^+$ ions in two segmented radio frequency traps. Ion traps have been used to demonstrate coherent manipulation of the quantum states of a small number of ion qubits. Segmented electrodes incorporated into the structure of these traps are designed to allow for the creation of multiple trapping regions and ion transport along the axis of the trap. The development of these techniques should open the possibility of greatly expanding the number of ion qubits under simultaneous coherent control.

The first trap is a micro-scale, planar, chip-top trap fabricated by Sandia National Laboratories. Scaling down the trap size presents new challenges including increased heating rates and reduced trap depth. Trap loading is via two step photo-ionization in the trapping region in the presence of a calcium atomic beam from an oven source. We have achieved ion lifetimes of $\sim$90 minutes in this trap and observed heating rates of $\sim$70 Ks^{-1}.

The second trap is also segmented but built on a sub-millimetre scale by the University of Liverpool. This is intended to be an intermediate step in adapting techniques of ion transport to micro-scale traps without the attendant high heating rates and low trap depths. We will report on trapping and initial experiments in this trap.

Finally we present details of a further three traps under preparation at Oxford, two of which are of a planar design.

Scalable, efficient ion-photon coupling with phase Fresnel lenses for large-scale quantum computing

D. Kielpinski, B. G. Norton, J. J. Chapman, E. W. Streed

Centre for Quantum Dynamics, Griffith University, Nathan, QLD 4111, Australia

Efficient ion-photon coupling is an important component for large-scale ion-trap quantum computing. We propose that arrays of phase Fresnel lenses (PFLs) are a favorable optical coupling technology to match with multi-zone ion traps. Both are scalable technologies based on conventional microfabrication techniques. The large numerical apertures (NAs) possible with PFLs can reduce the readout time for ion qubits. PFLs also provide good coherent ion-photon coupling by matching a large fraction of an ion's emission pattern to a single optical propagation mode (TEM_{00}). To this end we have optically characterized a large-numerical-aperture phase Fresnel lens (NA=0.64) designed for use at 369.5 nm, the principal fluorescence detection transition for Yb^+ ions. A diffraction-limited spot $w_0 = 350 \pm 15$ nm ($1/e^2$ waist) with mode quality $M^2 = 1.08 \pm 0.05$ was measured with this PFL. From this we estimate the minimum expected free space coherent ion-photon coupling to be 0.64%, which is twice the best previous experimental measurement using a conventional multi-element lens.

Fluorescence Imaging of Ultracold Neutral Plasmas

H. Gao, J. Castro, T. C. Killian

Rice University, Department of Physics and Astronomy, Houston, TX 77005, USA

Spatially-resolved fluorescence imaging of Ultracold Neutral Plasmas (UNP) produces a spectrum that is Doppler-broadened due to the thermal ion velocity and shifted due to the ion expansion velocity. Furthermore, sheet excitation of the plasma allows for localized analysis of the system without density variation. Using this technique, adiabatic cooling, electron-ion collisions, kinetic energy oscillations and velocity-changing collisions are studied for Ultracold Neutral Plasmas.

Trapped Rydberg Ions: From Spin Chains to Fast Quantum Gates

I. Lesanovsky[1], M. Müller[1], L.-M. Liang[2], P. Zoller[1]

[1] *Institute for Theoretical Physics, University of Innsbruck, and Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck, Austria*
[2] *Department of Physics, National University of Defense Technology, Changsha 410073, China*

We study the dynamics of Rydberg ions trapped in a linear Paul trap, and discuss the properties of ionic Rydberg states in the presence of the static and time-dependent electric fields constituting the trap. The interactions in a system of many ions are investigated and coupled equations of the internal electronic states and the external oscillator modes of a linear ion chain are derived. We show that strong dipole-dipole interactions among the ions can be achieved by microwave dressing fields. Using low-angular momentum states with large quantum defect the internal dynamics can be mapped onto an effective spin model of a pair of dressed Rydberg states that describes the dynamics of Rydberg excitations in the ion crystal. We demonstrate that excitation transfer through the ion chain can be achieved on a nanosecond timescale and discuss the implementation of a fast two-qubit gate in the ion chain.

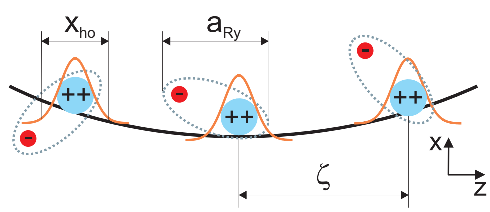

Figure 1: *Typical length scales in a chain of cold Rydberg ions in a linear Paul trap. The external trapping frequency is in the order of MHz with a corresponding oscillator length x_{ho} of approximately 10 nm. The interparticle spacing ζ, set by the equilibrium between the Coulomb forces among the ions and the external confinement, is typically about 5 $\mu\mathrm{m}$. The third length scale is the size of the Rydberg orbit a_{Ry}. Due to the scaling proportional to the square of the principal quantum number n it can assume values in the order of 100 nm and therefore become significantly larger than x_{ho}. In this regime the Rydberg ion cannot be considered as a point particle but rather as a composite object, and its internal structure must be taken into account.*

[1] M. Mueller, L.-M. Liang, I. Lesanovsky, P. Zoller, *Trapped Rydberg Ions: From Spin Chains to Fast Quantum Gates*, arXiv:0709.2849

Progress towards distribution of entanglement in an ion trap array

J. D. Jost[1], J. P. Home[1], J. M. Amini[1], C. Langer[2], R. Ozeri[3], D. Hanneke[1], J. J. Bollinger[1], R. B. Blakestad[1], J. W. Britton[1], D. Leibfried[1], S. Seidelin[4], N. Walrath[1], D. J. Wineland[1]

[1]*National Institute of Standards and Technology, Boulder, CO, U.S.A.*
[2]*Lockheed Martin, Huntsville, AL, U.S.A.*
[3]*Weizmann Institute of Science, Rehovot, 76100, Israel.*
[4]*University of Grenoble, France.*

Trapped atomic ions have now demonstrated the basic requirements for quantum information processing on small numbers of qubits, and the major remaining challenges are to improve operation fidelity and scale up these techniques to larger numbers of ions. This will require the ability to entangle, distribute, and perform subsequent entangling operations on multiple atomic ions in a large number of trapping sites. One possible scalable architecture is to move the ions themselves around an array of microtraps [1] [2]. This requires complex multi-zone traps, a high level of control of the electric fields used to move the ions, and the ability to address the different zones in a phase coherent way. In practice, ambient fluctuations in the electric field at the ion and imperfect control of electrode potentials mean that the ion’s motion is excited, which degrades the performance of two-qubit logic gates. In order to counteract these effects, coolant ions of a different species from the qubit can be simultaneously trapped, allowing re-initialization of the ground motional state of the ions prior to performing logic gates, without disturbing the quantum information.
We report on progress towards distribution of entangled atomic ions in a multi-zone trap array and the use of two species ion crystals ($^{24}Mg^{+}$ and $^{9}Be^{+}$) to prepare a well defined motional state after distribution.

[1]D. Kielpinski, C. Monroe and D. J. Wineland, Nature 417, 709 (2002)
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Individual addressing of trapped ions and coupling of motional and spin states using rf radiation

M. Johanning[1], A. Braun[1], N. Timoney[1], V. Elman[1], W. Neuhauser[2], Chr. Wunderlich[1]

[1]*Lehrstuhl Quantenoptik, Fachbereich Physik, Universität Siegen, Siegen, Germany*
[2]*Institut für Laser-Physik, Universität Hamburg, Hamburg, Germany*

We demonstrate for the first time two essential experimental steps towards realizing a novel concept for implementing quantum computing and quantum simulations with trapped ions[1]. The experiments were performed using the metastable $D_{3/2}$-state of laser cooled $^{172}Yb^{+}$-ions in a spatially varying magnetic field. When using π-transitions to repump ions from this metastable state back into the cycling cooling transition, the steady state cooling fluorescence rate is found to be proportional to the population in the "inner" $m = \pm 1/2$ states and stops because optical pumping populates the "outer" $m = \pm 3/2$ states. Population can be transfered coherently between inner and outer states by magnetic dipole transitions using rf radiation and single atoms can be addressed when the magnetic field and therefore the Zeeman splitting varies along the ion chain. Furthermore, the transition affects the ion's motional state: For the interaction in an inhomogeneous magnetic field, the Zeeman energy and thus the ion's equilibrium position may become state dependent and the coupling of internal and motional state is described by the *effective* Lamb-Dicke parameter η_{eff} and sidebands accompany the resonance[2].

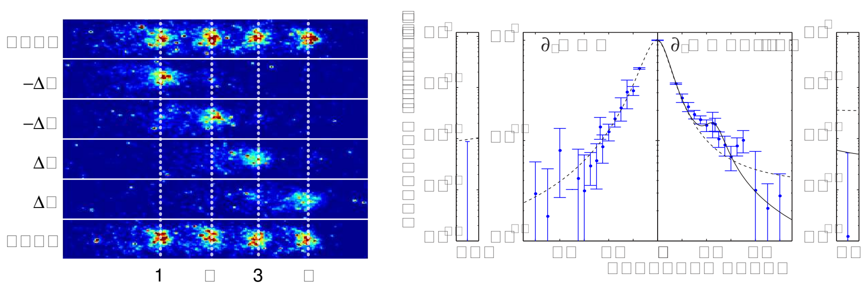

Figure 1: *a) Individually addressing single ions that are part of a linear Coulomb crystal composed of four ions. The uppermost and lowermost image are recorded without optical pumping (labeled 'NoOP') and all ions scatter light. For the intermediate pictures, the magnetic field direction is rotated allowing optical pumping, and the rf frequency was set to the expected resonance of one particular ion. Thus, all ions except one remain dark. b) Comparison of two symmetrized spectra recorded with a single ion in a constant magnetic field (left-hand side) and exposed to a magnetic field gradient (right-hand side). The dashed lines represent fits using a single Lorentzian (lhs and rhs), the solid line represents a fit using two Lorentzian lines (rhs). The motional sideband accompanying the spin resonance signifies coupling between the spin degree of freedom and the motion of the ion.*

[1]F. Mintert and C. Wunderlich, Phys. Rev. Lett. 87, 257904 (2001); C. Wunderlich, Laser Physics at the Limit (Springer, 2002), p. 261
[2]D. J. Wineland and W. M. Itano, Phys. Rev. A 20, 1521 (1979)

Observation of the Quadrupole Transition in a single cold $^{40}Ca^{+}$

B. Guo[1,2,3], H. Guan[1,2], Q. Liu[1,2,3], X. R. Huang[1,2], K. L. Gao[1,2,*]

[1]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics,Chinese Academy of Sciences, Wuhan 430071,China*
[2]*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*
[3]*Graduate School of the Chinese Academy of Sciences, Beijing 100080, China*
[*]*E-mail: klgao@wipm.ac.cn*

Trapped and cold $^{40}Ca^{+}$ ion is one of promising candidate of future optical frequency standards. We had measured the quadrupole transition of the $^2S_{1/2}$–$^2D_{5/2}$ of a single trapped and cold $^{40}Ca^{+}$ ion. Our experiments were performed with a single $^{40}Ca^{+}$ ion confined in a miniature Paul trap with a ring (r_0 = 0.8 mm), two endcaps ($2z_0$ = 2 mm) electrodes[1]. The pair of auxiliary rod electrodes was placed for compensating the stray electric field. For laser cooling, 397 nm and 866 nm lasers were carried out with commercial single-mode diode lasers (Toptica), which locking to Fabry-Perot interferometers and Optogalvanic (OG) signals respectively[2]. The laser at 729 nm for the clock transition $^2S_{1/2}$–$^2D_{5/2}$ was a Ti:sapphire laser (Coherent MBR-110), which locked to the high-finesse (F=3.5*10^6) ultra-low-expansion optical cavity. Single $^{40}Ca^{+}$ ion was loaded from neutral Ca atoms into the trap by electron ionization in the trap directly. The trapped single ion was laser cooled with the 397 nm and 866 nm lasers. The narrowing of fluorescence spectrum had been observed by minimizing the micromotion with optimizing the compensation voltages using the rf-photon correlation technique[3]. The quadrupole transition spectra were observed by the electron shelving method. Three magnetic field coils were used to generate an arbitrary magnetic field at the position of ion. The Zeeman components of $^2D_{5/2}$ were measured by pulse-light sequence.

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Temperature Dependence of Electric Field Noise Above Gold Surfaces

J. Labaziewicz, Y. Ge, D. R. Leibrandt, S. X. Wang, R. Shewmon, I. L. Chuang

Massachusetts Institute of Technology, Center for Ultracold Atoms, Department of Physics, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA

Dense arrays of trapped ions provide one way of scaling up ion trap quantum information processing. However, miniaturization of ion traps is currently limited by sharply increasing motional state decoherence at sub-100 μm ion-electrode distances. This decoherence has been demonstrated to be thermally driven, providing a plausible route to reduce it. In our experiment, we measure the heating rates out of the motional ground state of a single Sr^+ ion as a function of electrode temperature in $6 - 120$ K range. At 6 K, heating rates are observed to be as low as two quanta per second. The noise exhibits an approximate 1/f spectrum around 1 MHz, and grows rapidly with temperature as T^β for β from 2 to 4. The data fit a model with a continuous spectra of thermally activated random processes, and are consistent with microfabricated cantilever measurements of non-contact friction, but do not extrapolate to the DC measurements with neutral atoms or contact potential probes.

Frequency metrology on a single, trapped ion in the weak binding limit: The $3s_{1/2}$–$3p_{3/2}$ transition in Mg^+

M. Herrmann[1], V. Batteiger[1], S. Knünz[1], G. Saathoff[1], Th. Udem[1], T. W. Hänsch[1,2]

[1] *Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
[2] *Ludwig-Maximilians-Universität München, 80539 München, Germany*

Radio frequency ion traps allow to prepare a sample of cold ions subject to low systematic uncertainties, which enabled the most precise spectroscopic measurements ever made[1]. So far, virtually all absolute frequency measurements on trapped ions have been performed on very narrow transitions in the so-called strong binding limit, where the secular frequency of the ion exceeds the natural linewidth. In this case the spectrum consists of a carrier and a number of sidebands that can be addressed individually. Spectroscopy on the carrier eliminates Doppler and recoil shifts, an important prerequisite for the tremendous accuracies achieved. However, a range of interesting transitions have large linewidths that make it hard if not impossible to reach the strong binding limit. Examples include astrophysically relevant transitions[2] and the study of exotic nuclei by measuring isotope shifts of strong dipole transitions[3]. In this regime, heating and cooling distorts the observed line strongly, thereby limiting the spectroscopic accuracy. We developed a new measurement technique based on continuous sympathetic cooling of an ion chain and spatially resolved detection which overcomes these limitations and allows to observe a symmetric, well understood lineshape. To demonstrate the method we measured the absolute frequency of the $3s_{1/2}$–$3p_{3/2}$ transition in a single trapped Mg^+ ion at 280 nm (linewidth 41.8 MHz). This line is a so-called "anchor line" in the many-multiplet method used in the search for a drift of the fine structure constant α in quasar absorption spectra[4]. We were able to improve the uncertainty in the linecenter by two orders of magnitude over previous measurements[5]. Together with a recent measurement[6] on Ca^+ this is the first absolute frequency measurement on a trapped ion in the weak binding limit and the first to demonstrate an accuracy of 1% of the linewidth in this regime. The latter is required e.g. for a planned experiment that aims at studying the $^{11}Be^+$ halo nucleus via isotope shift measurements[3].

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[3] M. Zakova *et al.* Hyperfine Interact. **171** 189 (2006)
[4] J.K. Webb *et al.* Phys.Rev.Lett. **87** 091301 (2001)
[5] M. Aldenius *et al.* Mon.Not.R.Astron.Soc **370** 444 (2006)
[6] A.L. Wolf *et al.* arXiv:0804.4130v2 (2008)

Observation of Coulomb crystals in a cryogenic linear octupole rf ion trap

K. Okada[1], T. Takayanagi[1], M. Wada[2], S. Ohtani[3], H. Schuessler[4]

[1]*Department of Physics, Sophia University, 7-1 Chiyoda, Tokyo 102-8554, Japan*
[2]*Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*Institute for Laser Science(ILS), University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo, 182-8585, Japan*
[4]*Department of Physics, Texas A&M University, College Station, TX 77843, USA*

Large and small Coulomb crystals of laser-cooled Ca^+ ions have been observed in a cryogenic linear octupole rf ion trap. We have systematically investigated the changes of the shapes of the crystals by varying the axial static voltages and the asymmetric dc voltages (V_{dc}). For relatively small axial voltages, long prolate shapes of the ion crystals are observed when applying V_{dc}, while spherically symmetry shapes are observed for larger axial voltages (Fig.1). As shown in Fig.1 (a), even for a large number of ions the shell structures can be recognized inside the crystal. For a smaller number of ions (Fig.1 (b)), the shell structure is well resoved. The estimated interval between the shell structures is from 40 to 50 μm. Because of the small micromotion amplitudes in the large almost-field-free central region of the octupole ion trap, the clear shell structures are constructed. When a much larger number of ions are crystallized, the strange shape of the crystal emerges as shown in Fig.1 (c). Although the image is not clear, we recognize the dip along the axial direction. The reason of this property is possibly attributed to the characteristic sum potential in the radial direction[1].

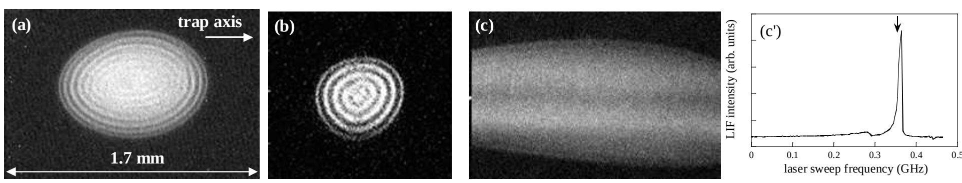

Figure 1: *Observed CCD images of the Coulomb crystals in the cryogenic linear octupole rf ion trap . The scale is same for the all images. The trapping parameters are $f_{rf} = 6.04$ MHz, $V_{ac} = 157$ V, and (a) $V_{z0} = 1.90$ V, $V_{dc} = 0.09$ V, (b) $V_{z0} = 3.40$ V, $V_{dc} = 0.60$ V, (c) $V_{z0} = 0.80$ V, $V_{dc} = 0$ V . The CCD image (c) was observed by setting the laser frequency to the position indicated by the arrow in the laser cooling spectrum of Fig.1 (c'). The number of ions are estimated to be (a) 1×10^3, (b) 4×10^2, and (c) $> 2 \times 10^3$ by assuming cylindrically symmetric crystals with a uniform number density of $n_0 \sim 10^6$ cm^{-3} derived from the Coulomb crystals composed of a small number of ions.*

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Cryogenic planar elliptical ion traps for quantum simulation

R. Clark, Z. Lin, Y. Ge, K. Diab, I. L. Chuang

Center for Ultracold Atoms, Research Laboratory of Electronics, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

Quantum simulations have the potential to calculate interesting properties of many-body systems, such as the phase diagrams of spin systems, that are intractable using classical computers. It has been shown that such a simulation may be implemented using a system of trapped ions manipulated by laser radiation [1]. In particular, a 2-D array of ions would enable the observation of interesting effects such as spin frustration. In this work we discuss the design and construction of a planar elliptical rf ion trap [2] that is capable of confining stable 2-D arrays of ions. The trap is operated at 4K to take advantage of the strong suppression of motional heating at low temperatures [3]. We present calculations of the secular potential of the trap and the predicted structure of ion crystals therein, as well as the expected micromotion as a function of the number of ions. We discuss the fabrication of the trap and the experimental system, including trap potentials, apparatus for measuring ion heating rates, and steps toward quantum simulations.

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Quantum Information Processing with Ions and Photons

S. Olmschenk, D. Hayes, D. N. Matsukevich, P. Maunz, D. L. Moehring, C. Monroe

Joint Quantum Institute, University of Maryland and National Institute of Standards and Technology, College Park, MD 20742

We demonstrate the entanglement of two atomic ions separated by about one meter.[1,2] Ultrafast pulses are used to simultaneous excite two individual ytterbium ions confined in separate vacuum chambers, and the resulting single photons emitted are coupled into optical fibers and combined on a beamsplitter. Due to the quantum interference of photon pairs, a coincident detection of the photons heralds the entanglement of the two trapped ions.[3,4]

Proper choice of the excitation and detection scheme allows for entanglement between the atomic state of an ion and either the frequency or polarization of the emitted photon. Optical frequency qubits also allow for the implementation of a quantum gate that could be used for scalable quantum computation.[5] We demonstrate entanglement for both schemes, and in the latter case, full quantum state tomography of the ion-photon and ion-ion entangled systems, as well as violation of a Bell inequality. In future work, alternate decay channels in the ytterbium ion may be harnessed to produce infrared photons (even near telecom wavelengths) to enable long-distance quantum communication, and perhaps the implementation of a loophole-free Bell inequality measurement.[4]

While this photonic linking requires identical photons be entangled with the emitting sources, the subsequent quantum interference is independent of these sources. Thus, this scheme may also be extended to entangle hybrid quantum systems such as atoms and quantum dots, exploiting the advantages of each for applications in quantum information processing.

We acknowledge support from IARPA under ARO contract and the NSF Physics at the Information Frontier Program.

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Microfabricated segmented ion trap for scalable quantum information science

S. A. Schulz, U. Poschinger, G. Huber, F. Ziesel, F. Schmidt-Kaler

Universität Ulm, Institut für Quanteninformationsverarbeitung,
Albert-Einstein-Allee 11, D-89069 Ulm, Germany

Miniaturized multi-segmented ion traps are a promising architecture for quantum information science in a scalable way[1]. The microfabrication of linear Paul traps allows partitioning the trap in various storage and processing regions for a large number of qubits. The individual control of many qubits is fundamental for the implementation of large-scaled quantum algorithms. The crucial requirement for a scalable quantum processor is the fast qubit transport between spatial separated trap regions.
Numerical optimization of the trap geometry allows the effective suppression of non-harmonic contributions to the radial and axial potential in microfabricated linear traps. The trap optimization is discussed and the numerical modelling of ion shuttling is investigated in the adiabatic[2] and non-adiabatic regime[3]. The fast transport in a non-adiabatic regime is optimized using classical optimal control theory to avoid the excitation of vibrational quanta.
A novel scalable segmented linear microtrap with two different adjacent zones and 62 independently controlled electrodes allows shuttling of ions with numerically designed potentials at trap frequencies of a few MHz. The microtrap is characterized using sideband spectroscopy on the narrow $S_{1/2}$ to $D_{5/2}$ transition of the $^{40}Ca^{+}$ ion. Coherent Rabi rotations, Ramsey spectroscopy and optical ground state cooling are demonstrated and the heating rate is determined. The applicability of the microtrap for scalable quantum information science is proven[4].
The combination of sideband spectroscopy with a single ion transport along the trap axis at constant axial frequency is demonstrated: Initially Doppler cooled, the ion is shuttled to a different trap region where sideband spectroscopy is performed. Shuttled back, the ions quantum state is revealed from a fluorescence measurement. Such operations are necessary for subsequent two-qubit quantum logic operations.

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Individual ion addressing using a magnetic field gradient in a surface-electrode ion trap

S. X. Wang, J. Labaziewicz, Y. Ge, I. L. Chuang

Center for Ultracold Atoms, Massachusetts Institute of Technology, Cambridge, USA

The ability to address individual ions is an important issue in using multiple trapped ions to perform quantum operations. Previous efforts have included using precisely focused laser beams aimed at only one ion at a time[1], which poses a significant technical challenge. An alternative is to use field-dependent transitions and a magnetic field gradient to shift the transition frequencies of ions as a function of position. This requires good stability of the local field in order to achieve desired fidelity of quantum operations. In a cryogenic Sr^+ ion trap we use the $5S_{1/2} \rightarrow 4D_{5/2}$ transition as an optical qubit, which can be Zeeman shifted using a bias field generated by external coils. We describe a scheme to create a local field gradient by integrating current sources onto a microfabricated surface-electrode trap, and present some initial experimental results. Taking advantage of the cryogenic environment, we also stabilize the field at the trap site using superconducting rings as flux shields. The rings can be integrated with the trap, simplifying implementation and improving alignment to the ions.

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Simulating a quantum magnet with trapped ions

A. Friedenauer, H. Schmitz, J. T. Glueckert, D. Porras, T. Schaetz

Max Planck Institut für Quantenoptik, Garching, Germany

We can not translate quantum behaviour arising with superposition states or entanglement efficiently into the classical language of conventional computers[1]. A universal quantum computer could describe and help to understand complex quantum systems. But it is envisioned to become functional only within the next decade(s). A shortcut was proposed via simulating the quantum behaviour of interest in another quantum system, where all relevant parameters and interactions can be controlled and observables of interest detected sufficiently well[1]. Instead of translating quantum dynamics into an algorithm of stroboscopic quantum gate operations to run them on a universal quantum computer, we want to continuously control and manipulate the spins, equivalent to the way nature evolves the system of our interest.

Our system for a feasibility study is a linear chain of magnesium ions[2]. External fields and interactions between the ions are simulated/controled via rf- and laser-fields respectively. To initialize our system, we cool up to three ions close to the axial-motional ground state($\bar{n} \simeq 0.02$). To calibrate our operational fidelities, we implemented a geometric phase gate and prepared an entangled Bell state of two ions with a fidelity exceeding 95%. Subsequently, we were able to simulate an adiabatic evolution[3] of two spins described by the Quantum-Ising-Hamiltonian from paramagentic into (anti)ferromagnetic order with an fidelity of 98%. We proof that this transition is driven by quantum (not thermal) fluctuations providing us even an entangled state with a lower bound for the fidelity of 88%. We discuss these results and comment on the possibilities to increase the size of our system.
Already a comparably small amount of simulation-spins, of the order of 30-50, are supposed to be sufficient to outperform classical computers. In addition, the fidelities of the proposed operations are predicted to be sufficiently high in state of the art experiments and do not have to be performed within very demanding fault tolerant limits for universal quantum computation[2].

Based on new ion-trap technology it seems to become feasible to scale the ion simulator to a larger amount of ions to realize trap arrays, allowing to investigate quantum simulations on two dimensional spin-grids, e.g. spin-frustration. Experts in the field allow us to hope, starting from arrays spanned by 10x10 ions, to provide new insight into quantum dynamics. We expect/hope to observe effects that represent Quantum-Phase Transitions for many-particle systems.

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Coherence of the metastable qubit in ^{40}Ca^{+} ions

K. Toyoda[1,2], S. Haze[1], R. Yamazaki[2], S. Urabe[1,2]

[1]*Graduate school of Engineering Science, Osaka University, Japan*
[2]*JST-CREST, Japan*

We have been investigating the possibility of using the metastable $3\,^2D_{3/2}$ and $3\,^2D_{5/2}$ states in ^{40}Ca^{+} ions as a qubit.[1,2] These states are separated from each other by 1.82 THz. In this scheme they are connected with a stimulated Raman transition induced by two infrared lasers at 850 and 854 nm. The two lasers (a titanium sapphire laser and a taper-amplified diode laser) are phase-locked to each other by using a passive-type optical frequency comb.[3]

In this poster we present our recent study on coherence between the two metastable states. The decay of the off-diagonal density matrix elements between the metastable states are measured by using the Ramsey method. By combining a spin-echo π pulse in a Ramsey sequence, a visibility decay time of 5.1 ms is obtained. This is sufficient for implementing simple quantum gate sequences. This work is an essential step for realization of a qubit using the two metastable states, and, to the best of our knowledge, is the first demonstration of coherent manipulation of the internal states separated by around a THz using phase-locked lasers.

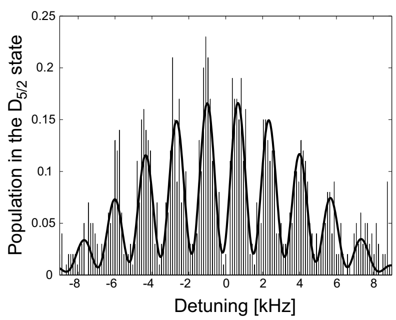

Figure 1: *Ramsey signal for the stimulated Raman transition between $3\,^2D_{3/2}$ and $3\,^2D_{5/2}$ states, taken with a pulse interval of 1 ms and a pulse duration of 98 μs.*

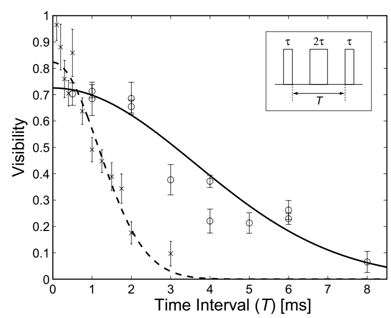

Figure 2: *Decay of the visibility of Ramsey signals. The circles represent visibility for spin-echo sequences, whereas the crosses represent visibility for normal sequences.*

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Robust creation of Dicke states of trapped ions by collective adiabatic passage

I. E. Linington[1,2], N. V. Vitanov[1,3]

[1] *Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria*
[2] *Department of Physics and Astronomy, University of Sussex, Falmer, Brighton, BN1 9QH, United Kingdom*
[3] *Institute of Solid State Physics, Bulgarian Academy of Sciences, Tsarigradsko chaussée 72, 1784 Sofia, Bulgaria*

We propose two novel techniques for the creation of maximally entangled symmetric Dicke states in a chain of trapped ions by using collective adiabatic passage. The techniques are applicable, with essentially the same level of complexity, to any number of ions and excitations. One of them [1] requires only a pair of chirped pulses from a single laser. By utilising a particular factorisation of the Hilbert space for multi-level ladders the problem is reduced to 'bow-tie' configuration energy-level crossings. By enforcing adiabatic evolution conditions, an arbitrary pre-determined collective Dicke state is created with high efficiency. This technique is naturally robust against fluctuations in the laser intensity and the chirp rate. This method may also be used to create number states of a collective vibrational mode of the ions. The other, closely related technique [2] uses global addressing of the entire chain by two pairs of delayed but partially overlapping laser pulses to engineer a collective adiabatic passage along a multi-ion dark state. This technique is a many-particle generalization of stimulated Raman adiabatic passage (STIRAP). It is therefore decoherence-free with respect to spontaneous emission and robust against moderate fluctuations in the experimental parameters. Because both techniques are very rapid, involving a single interaction step only, the effects of heating are almost negligible under realistic experimental conditions. We predict that the overall fidelity of synthesis of a Dicke state involving ten ions sharing two excitations should approach 98% with currently achievable experimental parameters.

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[2] I. E. Linington and N. V. Vitanov, Decoherence-free preparation of Dicke states of trapped ions by collective stimulated Raman adiabatic passage, Phys. Rev. A, in print (2008)

Coherent accumulation effects in the propagation of an ultrashort pulse train

A. A. Soares, L. E. E. de Araujo

Instituto de Física "Gleb Wataghin", Universidade Estadual de Campinas, Campinas - SP, 13083-970, Brazil

Absorbtion and dispersion can change the caracteristics of a resonant laser pulse propagating through an extended atomic medium. A weak ultrashort pulse (UP), whose temporal width is much shoter than the polarization decay time, is converted into an oscillatory function of time as it propagates[1]. When the medium is properly prepared by a preceding strong pulse, such a weak UP can experience amplification[2].

In this work we studied the propagation of an UP train through an extended collection of two- and three-level atoms (Figure 1). We worked in the weak field regime, with each individual pulse interacting with the medium in a perturbative way. Nevertheless, for repetitions periods shorter than the excited state lifetime, coherent accumulation of excitation between pulses will take place, and a strong excitation of the medium will occurs. Each pulse will find the medium in a different initial condition from that of the previous pulse. Thus, the pulse train propagation can't be described by linear dispersion law, and we solved the Maxwell-Bloch equations numerically.

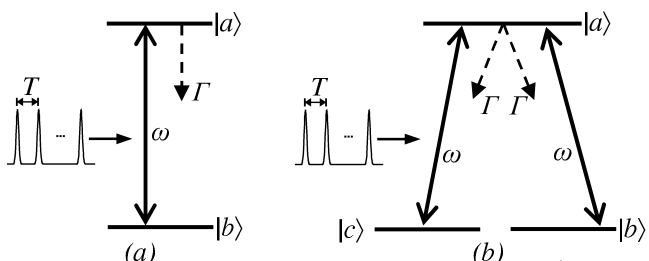

Figure 1: *The model atomic systems: (a) two-level system and (b) degenerate Λ system, interacting with a train of Gaussian UP with repetition period T. In both cases, the atoms are initially in their ground states.*

We observed that in the two-level system the pulse can experience both absorption and amplification. For the three-level configuration, after a large number of pulses, coherent accumulation by excitation of successives pulses leads to Electromagnetically Induced Transparency of the pulses and, at exit of the medium, the pulses have the same temporal shape than in the entrance of the atomic medium.

[1] L. Allen and J. H. Eberly, Optical Resonance and Two-Level Atoms (Dover, New York, 1987). M. A. Bouchene, Phys. Rev. A **66**, 065801 (2002)

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Synthesis of Sub-Single-Cycle Optical Pulse Train with Constant Carrier-Envelope Phase

A. H. Kung[1,2], W.-J. Chen[1], J.-M. Hsieh[1,3], C.-K. Lee[4], R.-P. Pan[5], C.-L. Pan[2]

[1] *Institute of Atomic and Molecular Sciences, Academia Sinica, Taiwan*
[2] *Department of Photonics, National Chiao Tung University, Taiwan*
[3] *Physics Department, National Taiwan University, Taiwan*
[4] *Institute of Electro-optical Engineering and Semiconductor Technology R&D Center, National Sun-Yat-Sen University, Taiwan*
[5] *Department of Electro-physics, National Chao Tung University, Taiwan*

Molecular modulation is a process in which the coherence of a molecule is driven with two intense laser beams to its maximum value. The strongly driven molecular coherence in turn modulates the incident laser frequency to produce a broad spectrum constituting many sidebands.[1] When these sidebands are all in phase a train of ultrashort laser pulses can be produced. A four- wave mixing cross-correlation scheme can be used to determine the temporal width of these pulses.[2]
With the help of two independently tunable pulse- amplified single-mode lasers we have generated in room temperature H_2 collinearly propagating Raman sidebands that have wavelengths that range from 1203 nm in the infrared to deep in the vacuum ultraviolet. The frequencies covered by these sidebands span over 4 octaves for a total of more than 70000 cm^{-1} in the optical region of the spectrum.[3] In this paper we describe the synthesis of periodic waveforms consisting of a train of pulses that are 0.83 cycles long and have an electric field pulse width of 0.44 fs using a subset of the sidebands we generated in H_2.[4] The pulse envelope FWHM is 1.4 fs. The wavelength of the sidebands used is from 1203 nm to 301 nm. We verify by cross- correlation measurements using four-wave mixing in Xe the characteristic of these pulses and that their carrier- envelope phase is constant when the pulses are synthesized from commensurate sidebands. The estimated overall shift of the carrier-envelope phase is less than 0.18 cycles from the first to the last pulse of nearly 10^6 pulses in the pulse train. These pulses will be useful for probing phase-dependent quantum processes in atoms and molecules that will complement time-resolved studies such as photoemission of inner shell electrons and Auger decay that have recently been demonstrated by probing with few-cycle to single cycle soft-x-ray pulses.[5]

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Filamentation properties of air with carrier-envelope offset controlled, few cycle light pulses

D. E. Laban, R. D. Glover, R. T. Sang, D. Kielpinski

Australian Attosecond Science Facility, Centre for Quantum Dynamics, Griffith University, Brisbane, Queensland, Australia

In this poster, we present work that explores the effects of filamentation as a function of the carrier-envelope phase for high power, few cycle light pulses. A filament is created when a high-powered optical field collapses due to the non-linear Kerr effect (self-focussing)[1]. The power density at this point is high enough to form a plasma in the air molecules through tunnel ionisation[2]. This alters the refractive index of the medium such that a stable equilibrium is obtained between self-focussing and self-defocussing which causes the length of the filament to exceed the Rayleigh length. The distance that self-focussing occurs at is dependent on the peak power of the pulse which, for a few cycle pulse, depends on the carrier-envelope phase. Within the filament many multi-photon ionisation events occur in the air molecules as well as self phase modulation, this results in a broad spectrum being observed at the end of the filament.

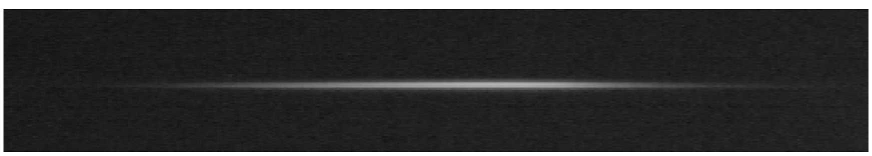

Figure 1: *A filament in air.*

We have observed filamentation in atmosphere using pulses generated by a Ti:Sapphire self mode-locked laser that is then intensified in a multi-pass amplifier and compressed in a neon filled hollow-core fiber. The laser system produces $<$6fs pulses with 0.4mJ energy and a spectral FWHM of 180nm at a central wavelength of 800nm. The carrier-envelope offset is controlled by using the f-2f interferometer technique that was devised by Hansch et al[3]. Experimental observations of changes to the properties of the filament, such as spectral broadening and the spatial onset, as a function of the carrier-envelope phase will be presented.

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Four-photon ionization of lithium.

I. A. Ivanov, A. S Kheifets

Research School of Physical Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia

We consider a process of four-photon ionization of lithium under the action of a 25 fs pulse of the Ti:sapphire laser (photon energy $\omega = 1.56$ eV). Our interest in the problem stems from recent experiments on the intense laser field ionization of magneto-optically trapped (MOT) Li atoms [1]. In these experiments certain puzzling features in the photoelectron spectra were observed which we try to simulate with the help of a direct solution of the time dependent Schrödinger equation (TDSE). We describe the field-free lithium atom in the ground state by solving a set of self-consistent Hartree-Fock equations. We adopt the single active electron approach and describe the one-electron excitations from the valence $2s$ shell in the frozen-core Hartree-Fock (FCHF) approximation.
To solve the TDSE we follow the strategy similar to that we have applied before for two-electron systems [2]. The TDSE is solved for the time interval $(0, T_1)$ corresponding to the duration of the pulse. The spectrum of photoelectrons is obtained as $f(\mathbf{p}) = |\langle \mathbf{\Psi_p^-} | \mathbf{\Psi(T_1)} \rangle|^{\mathbf{2}}$, where $\Psi(T_1)$ is solution of TDSE at the moment of the end of the pulse, $\Psi_{\mathbf{p}}^-$ is a scattering state of lithium with asymptotic electron momentum $\mathbf{p}$. To construct this state we rely again on the FCHF approximation. The resulting photoelectron distributions (as functions of the component of the momentum $p_{||}$ along the EM field) are shown in Figure 1 for various peak strengths of the EM field.

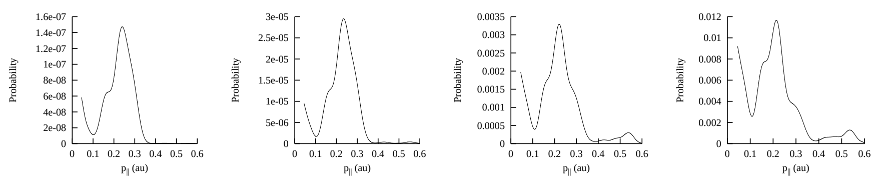

Figure 1: *Photoelectron momentum distribution as a function of* $p_{\|}$ *for various field strengths* $F_{\rm AC} = 0.001; 0.002; 0.004; 0.005$ *a.u.*

The prominent peak at about $p_{||} = 0.25$ a.u. in the electron distribution results from the 4-photon ionization of electrons from the ground state in the direction of the EM field. The presence of the central peak at $p_{||} = 0$ a.u. seemed puzzling in the experiment. Our results suggest, that considerable amount of photoelectrons may go in the direction perpendicular to the direction of the EM field, thereby creating central peaks in the distributions shown in the Figure 1.

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High harmonics generation from excited states of atomic lithium.

I. A. Ivanov, A. S Kheifets

Research School of Physical Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia

We present a calculation of the harmonics yield from the lithium atom exposed to an intense 3.5 μm midinfrared laser pulse. Lithium atom is described in the framework of the Hartree-Fock approximation. Time dependent Schrödinger equation (TDSE) for Li atom in the presence of the laser pulse is solved using the procedure we have applied before for two-electron systems [1], [2]. The TDSE is solved for the time interval $(0, 30T)$, where T is duration of an optical cycle of the laser field. Our calculation shows that a considerable increase of the yield of high harmonics generation (HHG) can be achieved if initially the atom is prepared in an excited $2p$.

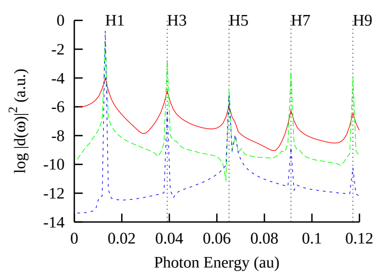

Figure 1: *Harmonics spectrum of Li from $2p$ state, peak strength of the EM field $F = 0.005$ a.u. (red) solid line, $F = 0.0025$ a.u. (green) long-dash line and from $2s$ state, $F = 0.005$ a.u. (blue) short-dash line.*

We show that this increase can be regarded as a resonant process due to appearance of a multiphoton resonance between the initial state and a quasienergy state. This conclusion follows from the approximative (neglecting depletion of the initial state) treatment of the HHG process using Floquet propagator for the description of the atomic evolution in presence of the laser pulse.

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All-fiber, octave-spanning supercontinuum source for versatile wavelength selection and powerful 243nm source

J. J. Chapman, M. G. Pullen, D. Kielpinski

Centre for Quantum Dynamics, Griffith University, Brisbane, Australia

A light source was generated with spectrum spanning more than an octave (900-1950nm) using fiber processes. Sub-picosecond pulses at 1550nm are produced by a mode-locked fiber laser. The pulses are expanded to more than 20ps using dispersion compensating fiber (DCF) to reduce non-linearities in the amplification stage. The chirped pulses are amplified using an erbium-doped fiber amplifier to an average power of 800mW. The amplified pulses are then sent through highly non-linear fiber (HNLF) for supercontinuum generation.

Using a diffraction grating this light was dispersed and the wavelengths 1110nm and 1944nm were recollected with power density 20uW/nm and 10uW/nm respectively. The collected light is sufficiently bright for re-amplification by a simple fiber preamplifier, before the main amplification stage using a power amplifier. This light will then be recompressed to achieve high peak-power, sub-picosecond pulses. The 1944nm pulses will then be frequency doubled three times with approximately 20% total conversion efficiency to produce up to 1W of 243nm light. The 1110nm light will also be amplified and recompressed for use in an ion-trap experiment.

New tools for coherent control of light emission

M. Ndong[1], R. Kosloff[2], H. Tal-Ezer[3], C. P. Koch[1]

[1] *Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany*
[2] *Department of Physical Chemistry and The Fritz Haber Research Center, The Hebrew University, Jerusalem 91904, Israel*
[3] *School of Mathematical Sciences, Tel Aviv University, Tel Aviv 69979, Israel*

Generation of coherent broadband UV emission by phase control of femtosecond multi-photon IR absorption was recently demonstrated.[1] The scheme is illustrated in Fig. 1: In atomic systems, rational phase shaping allows for rendering the intermediate two-photon resonance dark,[1,2] while optimizing the three-photon absorption which leads to the UV emission.
Our goal is to extend this scheme to molecules since more possibilities for control arise due to the internal degrees of freedom. Optimal Control Theory (OCT) will be employed where a state-dependant constraint [3] allows for suppressing population in a 'forbidden subspace'. In this formulation of OCT, an inhomogeneous Schrödinger equation is obtained. In order to solve it numerically, we derive a generalization of the Chebychev propagator. The formal solution of an inhomogeneous Schrödinger equation can be written in terms of functions of (known) operators acting on wavefunctions. Analogously to the case of the ordinary Schrödinger equation, the formal solution is amenable to polynomial approximations, using e.g. Chebychev polynomials. The propagator consists of the ordinary part plus an additional expansion in powers of the time step. We test the new propagator and present first applications.

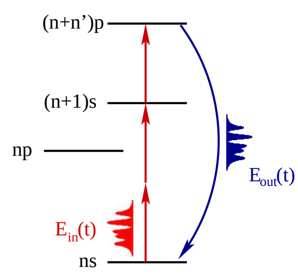

Figure 1: *Coherent broadband UV emission may be achieved by the absorption of three IR photons.*

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[2] D. Meshulach and Y. Silberberg, Nature **396**, 239 (1998).
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Ultrashort Pulse Generation with Zero Carrier Envelope Offset by using Broad Raman Sidebands

T. Suzuki[1,2], M. Katsuragawa[1,2]

[1] *Dep. of Appl. Phys. and Chem., Univ. of Electro-Comms, Tokyo, Japan*
[2] *JST-PRESTO, Saitama, Japan*

Recently, it was shown that a pair of intense laser fields near-resonant to a Raman transition, could strongly drive the Raman coherence in a far-off resonant three-level system, preparing a superposition state of two quantum states with maximal coherence which results in generation of broad Raman sidebands. In this study, we focus on the potential application of Raman sidebands for ultrashort pulse generation. Such ultrashort pulses have advantages which are the ultrahigh pulse-repetition rate, the tunability of the center frequency, and the controllability of the carrier envelope offset (CEO). The repetition rate corresponds to the frequency spacing which is determined by the Raman transition frequency, typically exceeding a terahertz. The center frequency and the CEO can be tuned by precisely controlling the frequencies of the pump fields. If we can make monocycle pulses from such Raman sidebands with zero-CEO, all the pulses have the same carrier envelope phase and can potentially form an asymmetrically oscillating, intense nanosecond pulse, as illustrated in Fig. 1.

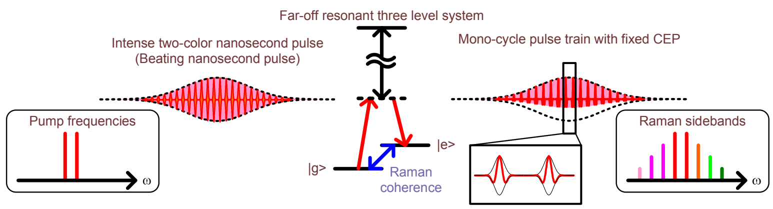

Figure 1: *Schematic of our procedure. Broad Raman sidebands with zero-CEO have a potential to form an intense, asymmetric nanosecond pulse.*

In this presentation, we show how we generate a broad sideband spectrum and control its CEO to zero. We drove a Raman coherence by using two intense nanosecond pulses generated from a dual-wavelength injection-lock pulsed Ti:Sa laser. We used pure-rotational Raman transition of $J = 0$ to 2 (10.6 Thz) in parahydrogen molecules at liquid nitrogen temperatures. The sideband spectrum can satisfy the zero-CEO condition when the two pumps were adjusted to have the appropriate frequencies. In order to broaden the sideband spectrum and measure the CEO, we further introduced a second harmonic (SH) of one of the two pump fields. Consequently, sidebands of over 50 components were generated, spanning from infrared to ultraviolet with the equidistant frequency spacing of 10.6 THz. We measured the CEO of less than 1 GHz by making use of the idea of the f-$2f$ self-reference method. We will also show recent progress of spectral-phase compensation of the sidebands to give monocycle pulse train resulting in an asymmetric nanosecond pulse which has various potential applications in physical and chemical researches.

Orientation-Dependent Behavior of Strong-Field Ionization Rates for Laser-Irradiated Diatomics

P. E. Pyak[1,2], V. V. Kim[1], V. I. Usachenko[1,2]

[1]*Institute of Applied Laser Physics UzAS, Tashkent, Uzbekistan*
[2]*Department of Physics, National University of Uzbekistan, Tashkent, Uzbekistan*

The strong-field process of above-threshold ionization (ATI) in laser-irradiated N_2, O_2 and F_2 molecules depending on molecular axis orientation with respect to incident laser field polarization is theoretically studied for various laser intensities. The incident laser intensity I is supposed to vary within a broad range corresponding to a large scale of the so-called Keldysh parameter γ extending between too small values $\gamma \ll 1$ (corresponding to tunneling regime of ionization) and too large values $\gamma \gg 1$ (corresponding to multiphoton regime of ionization).

The problem is addressed within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA) assuming the validity of *single-active electron* consideration and LCAO-MO method to model an initial molecular wavefunction as a set of one-electron molecular valence shells. Unlike alternative SFA-based consideration[1], the currently applied approach essentially exploits the *density functional theory* method of accurate composition of initial (laser-free) molecular state using the GAUSSIAN-03 code[2]. Such a composition allows to reproduce the correct ordering of at least three outer valence shells including the *highest-occupied molecular orbital* (HOMO) and provide accurate values of respective binding energy[3].

The resulting total molecular ionization rates were found to be very sensitive to spatial orientation of molecular axis with respect to incident laser field polarization. The form of such orientation-dependent behavior has been found to be mostly dependent on orbital and bonding symmetry of initial (laser-free) molecular state corresponding to HOMO. For example, the ionization rate calculated for N_2 (with $3\sigma_g$ HOMO) proved to have an orientation dependence quite different from that calculated for F_2 (with $1\pi_g$ HOMO). Meantime, the extent of how much pronounced the orientation dependence is for either of diatomics proved to be strongly dependent on incident laser intensity. Namely, the orientation dependencies of N_2 and F_2 ionization rates demonstrate a similar intensity-dependent behavior being most pronounced within the region of moderate laser intensity (viz., $\gamma \approx 1$ or $I \approx 2 \cdot 10^{14} W/cm^2$ for $\lambda = 800$ *nm*). Accordingly, these orientation dependencies become considerably less pronounced within either low-intensity (viz., $\gamma > 1$ or $I < 2 \cdot 10^{14} W/cm^2$) or high-intensity (viz., $\gamma < 1$ or $I > 2 \cdot 10^{14} W/cm^2$) domains. For the former intensity domain the behavior of revealed orientation dependencies confirms the respective earlier VG-SFA findings[1], whereas, for the latter domain, it rather agrees with opposite prediction of alternative MO-ADK calculations[4].

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On Contribution from Inner Molecular Shells to No Suppression in Strong-Field Ionization of F_2

P. E. Pyak[1,2], V. V. Kim[1], V. I. Usachenko[1,2]

[1]*Institute of Applied Laser Physics UzAS, Tashkent, Uzbekistan*
[2]*Department of Physics, National University of Uzbekistan, Tashkent, Uzbekistan*

The highly multiphoton phenomenon of strong-field above-threshold ionization (ATI) in F_2 molecule is addressed within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA). Contrary to prediction[1], the total molecular ionization rate observed in experiments[2] for F_2 does not show a suppression as compared to its atomic counterpart Ar of nearly equal ionization potential. Unlike alternative VG-SFA consideration[1], the currently applied approach is essentially based on the *density functional theory* method of accurate numerical composition of initial (laser-free) molecular state using the GAUSSIAN-03 code[3]. Such a composition allows to reproduce the accurate binding energies of at least three outer valence shells including the *highest-occupied molecular orbital* (HOMO) using the model LB_α intramolecular binding potential, which incorporates both the *exchange* (factorized by α) and *correlation* (factorized by β) *LSDA*-potentials[4].
The resulting total ionization yields calculated for F_2 are well consistent with experiment and demonstrate no suppression versus Ar ionization. Moreover, the calculated partial contributions of ionization from separate inner molecular valence shells (such as $1\pi_u$ and $3\sigma_g$) suggest that predominant contribution to F_2 ionization is to be always from the $1\pi_g$ HOMO corresponding to the outermost valence shell. The latter is in a contradiction to alternative consideration[4] based on time-dependent density functional theory (TD-DFT), which attributed the mechanism of no suppression in F_2 ionization to an exceptionally enhanced ionization from $3\sigma_g$ inner shell, which may contribute comparably or even predominantly within the high-intensity laser field domain $I \geq 3 \cdot 10^{14} W/cm^2$. Such an interpretation seems to be at least insufficient leaving unexplained the reason, for which the relative contribution from similar $3\sigma_g$ inner shell in O_2 is to be always negligible that results in a high suppression observed[2] in ionization of O_2 versus its atomic counterpart Xe. Our present VG-SFA results assuming a predominant contribution from $1\pi_g$ ionization (similar to it occurs in O_2) thus suggest quite a different interpretation for no suppression in F_2 ionization. The phenomenon is presently explained by the closed-shell nature of $1\pi_g$ in F_2 implying a domination of the correlation *LSDA*-potential (viz., $\alpha = 0.988$ versus $\beta = 1$), in contrast to the open-shell $1\pi_g$ in O_2, to which the exchange *LSDA*-potential proved to contribute predominantly (viz., $\alpha = 1.745$ versus $\beta = 1$).

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Driven cold atoms as a model system for nonequilibrium dynamics : Dynamic phase transition

Myoungsun Heo, Yonghee Kim, Jina Park, Wonho Jhe

Department of Physics, Seoul National University , Seoul, Korea

Strongly driven nonlinear oscillators show a variety of interesting phenomena such as period doubling, bifurcation, chaos, and so on. Recently fluctuational paths in such nonequilibrium systems have revealed several distinct phenomena from those in equilibrium systems such as breaking of time-reversal symmetry[1] , lack of detailed balance[2], universal scaling laws in activation energies[3], etc. However these studies have been done so far in the systems having only single oscillator. Using cold atomic systems, we can study the effects of collective interactions on nonequilibrium systems. We previously investigated spontaneous breaking of population symmetry between identical attractors[4]. Here we further study its critical properties by measurements of relevant critical exponents. Obtained critical exponents reveals the long-range features of the phase transition and the interactions. In addition, by adding oscillating bias field, we observe new kinds of phase transition called dynamic phase transition[5].

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Femtosecond laser frequency comb for precision astrophysical spectroscopy

C.-H. Li[1,2], A. J. Benedick[3], C. E. Cramer[1,2], P. Fendel[3,4], A. G. Glenday[1,2], F. X. Kärtner[3], D. F. Phillips[1], D. Sasselov[1], A. Szentgyorgyi[1], R. Walsworth[1,2]

[1]*Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, 02138, USA*
[2]*Dept. of Physics, Harvard University, Cambridge, MA, 02138, USA*
[3]*Department of Electrical Engineering and Computer Science and Research Laboratory for Electronics, Massachusetts Institute of Technology, Massachusetts 02139, USA*
[4]*MenloSystems INC, Germany*

Spectroscopy is a crucial tool for cosmology and the search for extrasolar planets. Broadband frequency combs have revolutionized precision spectroscopy in the laboratory with frequencies determined to better than one part in 10^{15}, good long-term stability and reproducibility. However, their application to astrophysics requires increasing the comb-line spacing by at least 10-fold from today's high repetition rate sources operating at about 1 GHz. We report the successful test of a 40-GHz comb generated from a 1-GHz source combined with a Fabry-Pérot cavity, without compromise on long-term stability, reproducibility and resolution. The application of this novel technique to astrophysics should allow more than a 10-fold improvement in Doppler-shift sensitivity, with significant impact to many fields, including the search for extrasolar Earths, the direct measurement of the universe expansion and the detection of the temporal variation of physical constants.

Photon localization and Dicke superradiance in atomic gases

E. Akkermans[1,2], A. Gero[1], R. Kaiser[3]

[1]*Department of Physics, Technion Israel Institute of Technology, 32000 Haifa, Israel*
[2]*Department of Applied Physics and Physics, Yale University, USA*
[3]*Institut Non Linéaire de Nice, UMR 6618 CNRS, France*

Photon propagation in a gas of N two-level atoms at rest, enclosed in a volume L^3, with a uniform density n, is studied using the effective Hamiltonian

$$H_e = \left(\hbar\omega_0 - i\frac{\hbar\Gamma_0}{2}\right) S_z + \frac{\hbar\Gamma_0}{2}\sum_{i\neq j} V_{ij} S_i^+ S_j^-$$

which describes photon mediated atomic dipolar interactions. $S_{i,z}^{\pm}$ are atomic operators. The density $P(\Gamma)$ of photon escape rates is determined from the spectrum of the $N \times N$ random matrix $\Gamma_{ij} = \sin(x_{ij})/x_{ij}$, where x_{ij} is the dimensionless random distance between any two atoms. The disorder strength is defined by the dimensionless parameter $W = \frac{\pi}{2}\frac{\lambda}{L}\frac{N}{N_\perp}$ where $N_\perp \equiv (k_0 L)^2/4$ is the number of transverse photon modes. A quantitative characterization of $P(\Gamma)$ is obtained using the function $C(L,W)$ defined between 0 and 1 by $C(L,W) = 1 - 2\int_1^\infty d\Gamma \;\; P(\Gamma)$. It measures the relative number of states having a vanishing escape rate. At finite size, we expect $C(L,W)$ to have a scaling form namely to be a function of $L/\xi(W)$ alone. We have verified this scaling behavior over a broad range of size and disorder when results are plotted as a function of $\pi^2 N/N_\perp$, see Fig. 1.

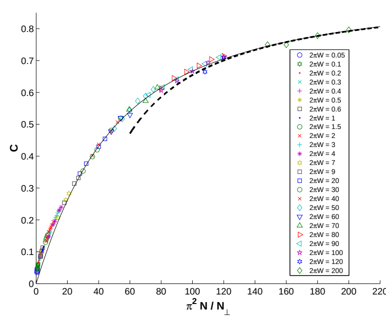

Figure 1: *Scaling behavior of $C(L,W)$ when plotted as a function of the parameter $\pi^2 N/N_\perp$. The continuous line is a fit obtained from a stochastic model and the dashed line results from microscopic calculations in the asymptotic limit $N \gg N_\perp$.*

We explain these results (see Fig. 1) using microscopic calculations together with a stochastic model which emphasizes the role of cooperative effects in photon localization and provides an interesting relation with statistical properties of "small world networks".

Motion-Induced Resonance: Toward a New Atom Manipulation Technique Using Periodic Structures

A. Hatakeyama, Y. Kobayashi, T. Ino

Department of Applied Physics, Tokyo University of Agriculture and Technology, Japan

Interactions of particles with periodic structures have been studied for a long time and used in various applications. Only a few are mentioned here: atomic beam diffraction techniques for surface analysis[1]; atom mirrors using periodically magnetized surfaces[2]. These applications are mostly concerned with the change or control of atomic motional states, but periodic structures can actually be used to induce resonance transitions of atomic internal states. We have been investigating this kind of resonance, with an aim of developing a new type of atom manipulation technique useful especially near surfaces. The experimental system we have used so far is Rb vapor confined in a thin cell to which a spatially periodic magnetic field is applied with an array of parallel current-carrying wires. Magnetic resonance transitions were induced by atomic motion through the periodic field, providing resonance spectra similar to ones obtained with the standard magnetic resonance technique[3]. Resonances induced by the combination of atomic motion and the temporal oscillation of the periodic field were also studied[4].

The above "prototype" experiments in a relatively simple setup using the thin cell of Rb vapor are now followed by ongoing experiments in more elaborate setups for investigating the change of the atomic momentum associated with the internal transition. Well controlled atomic beams in a vacuum, such as an atomic fountain of laser cooled atoms, interact with several types of periodic magnetic structures, for example, a stack of arrays of parallel current-carrying wires and a periodically magnetized transparent film enabling optical control of atoms as well. Resonance peaks much sharper than in the cell experiment have been obtained.

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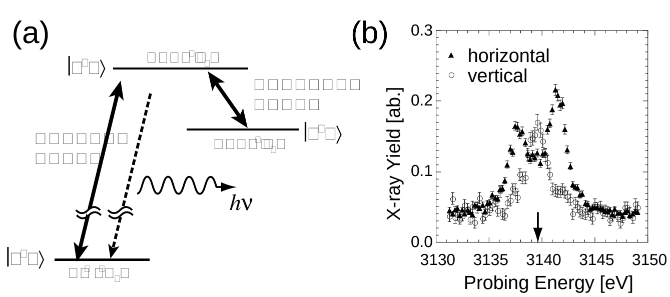
Dressed Atom Formation by Periodic Crystal Fields

Y. Nakano[1], T. Azuma[1], A. Hatakeyama[2], Y. Nakai[3], C. Kondo[4], K. Komaki[4,5], Y. Yamazaki[4,5], E. Takada[6], T. Murakami[6]

[1]*Department of Physics, Tokyo Metropolitan University, Tokyo, Japan*
[2]*Department of Applied Physics, Tokyo Univ. of Agriculture and Technology, Tokyo, Japan*
[3]*Radioactive Isotope Physics Laboratory, RIKEN Nishina Center, Saitama, Japan*
[4]*Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan*
[5]*Atomic Physics Laboratory, RIKEN, Saitama, Japan*
[6]*National Institute of Radiological Sciences, Chiba, Japan*

We investigated the coherent control of a quantum system by a periodic crystal field instead of a laser field. When fast ions propagate though a crystal, they experience a temporally-oscillating field originated from the periodic crystalline structure. As is the case for the photon irradiation, the crystal field induces the electronic transition of the ions at the resonant frequency. This unique process is called Okorokov effect or resonant coherent excitation (RCE). Since the oscillating field consists of numerous frequency components, a double resonance can be realized by adopting two of them simultaneously to the resonance. In three-dimensional RCE (3D-RCE)[1], two frequency components can be scanned independently by the tilt angles of the crystal θ and ϕ with respect to the ion velocity. We performed the two-color experiments on the three-level Λ system of helium-like Ar^{16+} ions. One frequency coupled $1s2p(2^1\mathrm{P})$-$1s2s(2^1\mathrm{S})$ and the other probed $1s^2(1^1\mathrm{S})$-$1s2p(2^1\mathrm{P})$ as illustrated in Fig. 1(a). In the present configuration, $|1^1\mathrm{S}\rangle$-$|2^1\mathrm{P}\rangle$ and $|2^1\mathrm{P}\rangle$-$|2^1\mathrm{S}\rangle$ are the electric dipole transition in the x-ray and vacuum ultra violet (VUV) energy region, respectively. Figure 1(b) shows the yields of x-ray emission from the Ar^{16+} ions to the horizontal and vertical directions which accompany the radiative decay of the probed states. In the horizontal direction, we observed a well resolved doublet around the transition energy of $|1^1\mathrm{S}\rangle$-$|2^1\mathrm{P}\rangle$ (3139.56 eV). This doublet is well-known as the Autler-Townes doublet which proves the strong, coherent interaction between the ions and the coupling field. Furthermore, we obtained a singlet peak in the vertical direction because the coupling field in the present experiment was linearly polarized in the vertical direction. Our result demonstrated that the internal state of traveling ions are coherently controlled by the periodic field on its way through the crystal.



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Negative Refractive Index Without Absorption

R. M. Rajapakse[1], S. F. Yelin[1,2]

[1] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[2] *ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138*

we suggest a modified level scheme of excitons or polar molecules to study negative refractive index without absorption. We use quantum interference effects to suppress absorption and introduce chirality, and attempt to find optimal densities of media that will give us negative refractive index without absorption.

Decoherence in molecular wave packet through sub-Planck scale structure

S. Ghosh, U. Roy, D. Vitali

Dipartimento di Fisica, Università di Camerino, I-62032 Camerino, Italy

A phase space structure associated with sub-Planck scale $(<< \hbar)$ can exist in non-local quantum superposition or Schrödinger cat states. Zurek[1] showed that appropriate superpositions of some of these states can lead to sub-Planck scale structures in phase space. These structures are very sensitive to decoherence. A cavity QED realization involving the mesoscopic superposition the so-called "compass states" has already given [2]. They have been also analyzed in the Kirkwood-Rihaczek representation [3] and in the form of entangled cat states [4]. Recently, the existence of those structures have been found in the time evolution of molecular wave packets [5]. Here, we study the effect of the decoherence due to the coupling with vibrational levels on these sub-Planck scale structures in molecular wave packets. The time evolution of these wave packets is investigated under the influence of an environment modeled, as usual, by a set of harmonic oscillators. We shall determine the master equation describing the reduced dynamics of the wave-packet and analyze the robustness of the sub-Planck structures against decoherence.

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Towards a Random Laser with Cold Atoms

W. Guerin, F. Michaud, R. Kaiser

Institut Non Linéaire de Nice, CNRS and Université de Nice Sophia-Antipolis,
1361, route des Lucioles, 06560 Valbonne, France

Since the Letokhov’s seminal paper[1], random lasers have received increasing interest in the past decade. Random lasing occurs when the optical feedback due to multiple scattering in the gain medium itself is sufficiently strong to reach the lasing threshold. So far, it has been observed in a variety of systems[2], but many open questions remain to be investigated, for which better characterized samples would be highly valuable. A cloud of cold atoms could provide a promising alternative medium to study random lasing, allowing for a detailed understanding of the microscopic phenomena and a precise control on essential parameters such as particle density and scattering cross-section. We report our progress towards this goal.

As a first step, we have used a standard cavity to trigger laser oscillation with a magneto-optical trap (MOT) of rubidium 85 as gain medium. We present the realization of such a cold-atom laser, that we demonstrated with three different gain mechanisms, depending on the pumping scheme. By pumping near resonance, Mollow gain[3] is the dominant process and gives rise to a laser emission, whose spectrum is large (of the order of the atomic natural linewidth), whereas by pumping further from resonance, Raman gain between Zeeman sublevels produces a weaker, spectrally sharper laser[4]. At last, by using two counter-propagating pump beams, degenerate four-wave mixing (FWM) generates a laser with a power up to 300 μW. We have studied the main properties of these different lasers[5]. Mollow and Raman gains seem promising mechanisms for the search of random lasing in cold atoms, because they can produce high gain at frequency slightly detuned from the pump, allowing to distinguish between stimulated photons from the laser mode and elastically scattered photons from the pump beam. The FWM laser could find application in other fields, such as quantum optics, by making use of the correlation between the phase-conjugated waves.

As strong pumping reduces the atomic scattering cross-section, combining these gains with multiple scattering is a challenging problem. An independent measure of the scattering rate in presence of pumping should allow to evaluate the threshold of random lasing, which in our case will be a critical (on-resonance) optical depth for the cold atom cloud. We report the status of our current investigation on this question. Preliminary theoretical evaluation with Mollow gain seems to indicate that an optical depth of the order of 100 might be enough, which is reachable with the current state-of-the-art laser-cooling techniques.

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Laser Spectroscopy of Scandium Isotopes and Isomers

Yu. P. Gangrsky[1], K. P. Marinova[1], S.G. Zemlyanoi[1], M. Avgoulea[2], J. Billowes[2], P. Campbell[2], B. Cheal[2], B. Tordoff[2], M. Bissel[3], D. H. Forest[3], M. Gardner[3], G. Tungate[3], J. Huikari[4], H. Penttilä[4], J. Äystö[4]

[1]*FLNR Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia*
[2]*Shuster Building, University of Manchester, Manchester M13 9PL, UK*
[3]*School of Physics and Astronomy, University of Birmingham, B15 2TT, UK*
[4]*Accelerator Laboratory, University of Jyväskylä SF-405 51, Finland*

Collinear laser spectroscopy experiments on the ScII transition 3d4s $^3D_2 \rightarrow$ 3d4p $^3F_3$ at $\lambda \approx 363.1$ nm were performed on the $^{42-46}Sc$ isotopic chain using an ion guide isotope separator with a cooler-buncher. The hyperfine structures and isotope shifts of five scandium isotopes (Z = 21) in the mass region $42 \leq A \leq 46$, with isomeric states in $^{44,45}Sc$, have been measured.[1,2]
Radioactive isotopes were produced in a fusion ion guide by irradiating a ^{45}Sc target in reactions of the type (d,p), (p,pxn), (p,p$'$) using 15 MeV deuterons and 25–48 MeV protons at 5-10 μA. Laser light was provided by a frequency-doubled Spectra-Physics 380D dye laser locked to a chosen molecular iodine absorption line.
The limits of possible variation of the mean squared charge radii in the scandium isotopic chains were deduced from measured isotope and isomer shifts. For the studied isotopes of the odd-Z element Scandium the magnetic dipole and electric quadrupole hyperfine coefficients A and B of both lower, 3d4s $^3D_2$, and upper, 3d4p $^3F_3$, states are obtained from the hyperfine structures using a χ^2 minimization fitting procedure. The results obtained from these data for the magnetic dipole and electric quadrupole moments of $^{43,44,44m,46}Sc$ isotopes are in good agreement with those summarised by Stone,[3] but has better accuracy. The nuclear moments $\mu(^{45m}Sc)$ and $Q_s(^{45m}Sc)$ are deduced for the first time. The unusually large quadrupole moment of the isomeric state of ^{45}Sc is the most striking feature of the present data.

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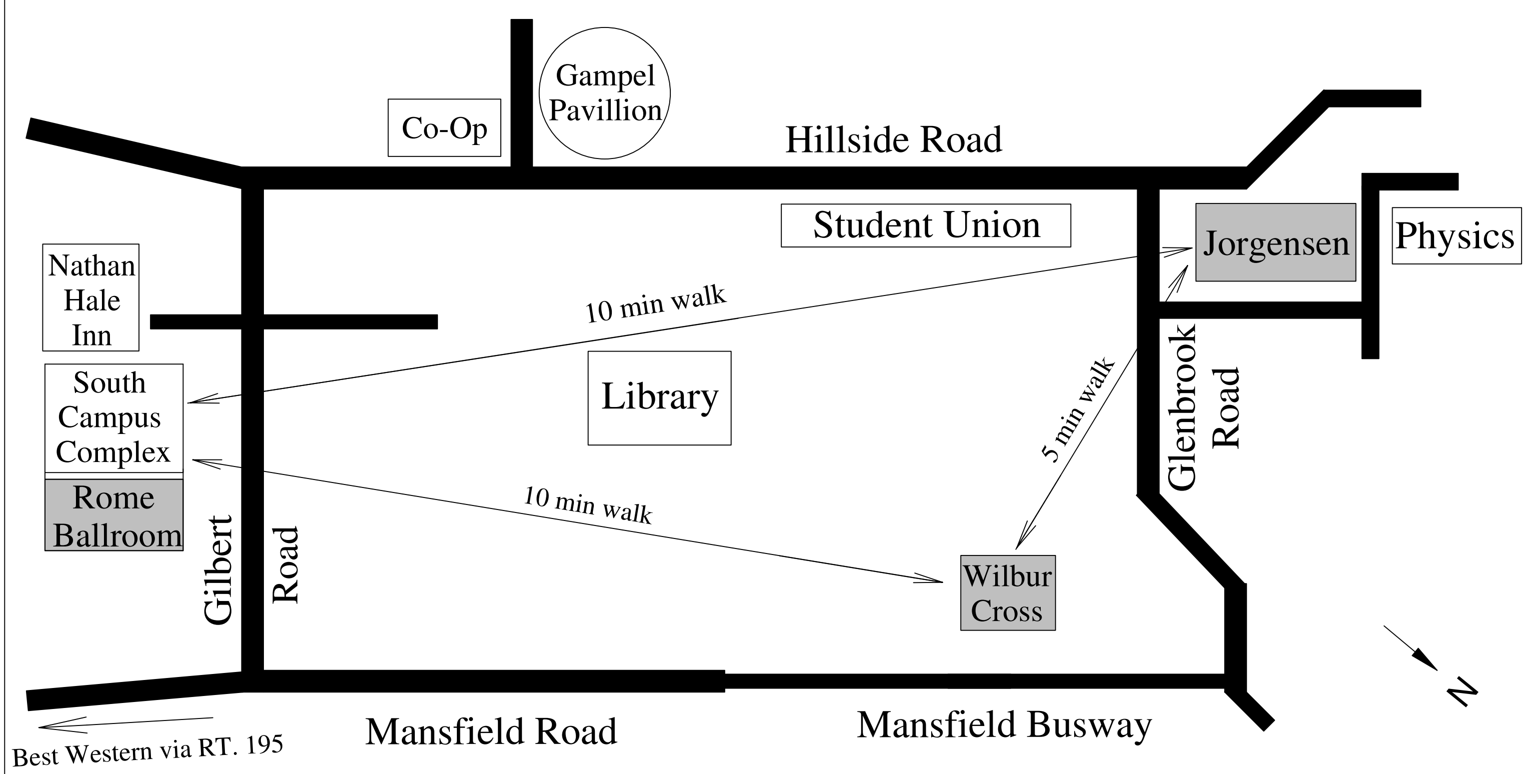

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