Invited Talks

Jorgensen Auditorium, Jorgensen Center

Nobel Laureate Sessions, I & II

Precision Measurements

Atomic Clocks

Quantum Information

Trapped Ions

Quantum Optics & Cavity QED

Hot Topics I

Public Lecture

Bose Gases

Fermi Gases

Optical Lattices

Cold Molecules

Hot Topics II

Mesoscopic Quantum Systems

Ultrafast Phenomena

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

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

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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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When is a Quantum Gas a Quantum Liquid?

E. A. Cornell

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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

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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

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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

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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

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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.

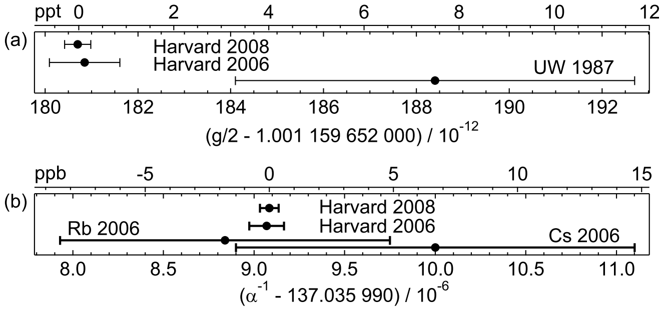

Figure 1: *New measurements of the dimsionless magnetic moment of the electron (a) and of the fine structure constant (b).*

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

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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

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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

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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

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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.

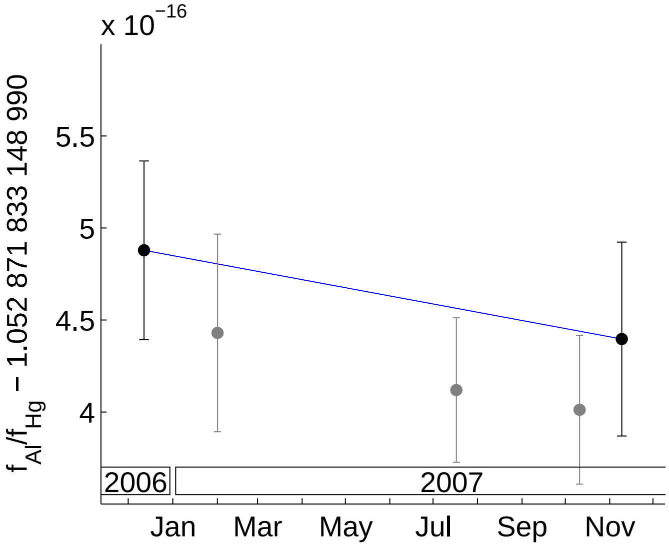

Figure 1: *History of frequency ratio measurements grouped by month. The line connects the first point to the last one with a slope of* $(-5.3 \pm 7.9) \times 10^{-17}$*/ year.*

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

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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

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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

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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

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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

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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

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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

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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

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[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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Pseudo-Spin Squeezing on an Atomic-Clock Transition

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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

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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.

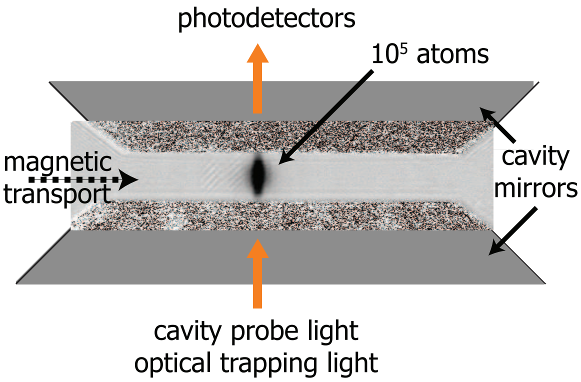

Figure 1: *The paradigmatic system of a mechanical oscillator coupled to a single mode of light is realized at a macroscopic level by trapping a large atomic ensemble within a high-finesse optical resonator. A single mode of collective atomic motion is actuated by the cavity field and measured by its 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

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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 $>2 \times 10^{14}$ 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

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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

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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].

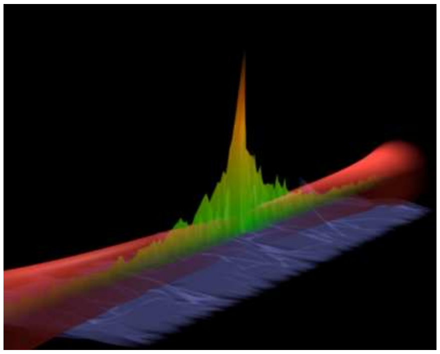

Figure 1: *Observation of Anderson localisation in 1D with an expanding Bose-Einstein Condensate in the presence of a 1D speckle disorder.*

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Anderson localization of a non-interacting Bose-Einstein condensate

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M. Modugno, M. Inguscio

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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.

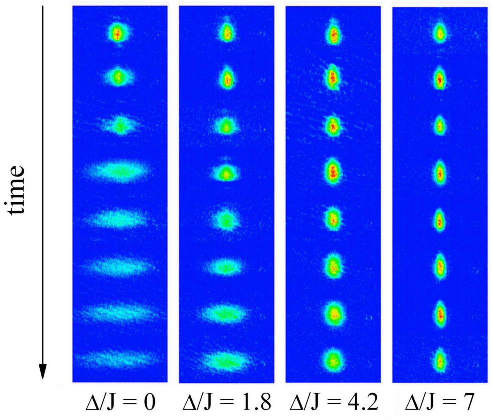

Figure 1: *Images of the BEC expanding in the bichromatic lattice for different ratios between disorder amplitude* Δ *and tunnelling energy* J*. The crossover between ballistic expansion and localization is clearly shown.*

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Ultracold Physics at UConn, Including Spectra of Ultracold Molecules

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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

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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

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[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

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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].

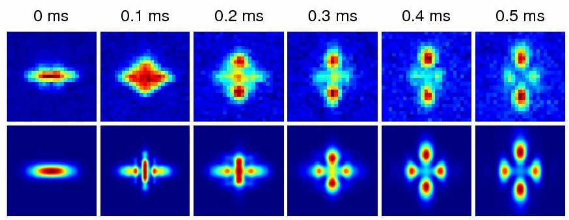

Figure 1: *Dipolar collapse dynamics for different hold times in the trap. Upper line: experiment, lower line: theory.*

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1D Bose gases

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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

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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

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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]

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

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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

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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

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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

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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

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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

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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

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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

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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

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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].

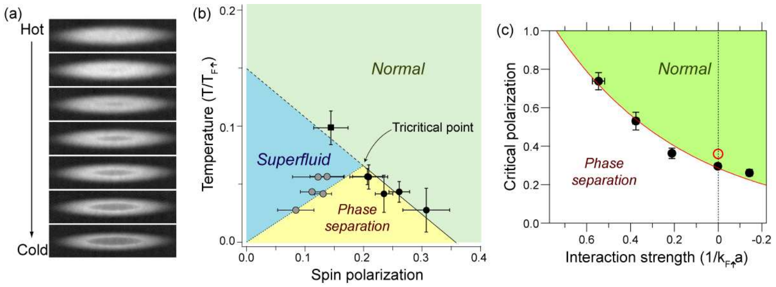

Figure 1: *(a) Phase transition in a trapped Fermi mixture. in situ distribution of column density difference for various temperatures. Phase diagram (b) with resonant interactions and (c) in the plane of interaction strength and spin polarization.*

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Towards Quantum Magnetism with Ultracold Quantum Gases in Optical Lattices

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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

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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

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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 temepraturе $T = 300$ 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.

This work was supported by the National Science Foundation and a Sloane Research Fellowship.

Cavity Optomechanics: Backaction Cooling of Mechanical Oscillators

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The possibility to observe quantum phenomena of macroscopic objects has been a longstanding 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.

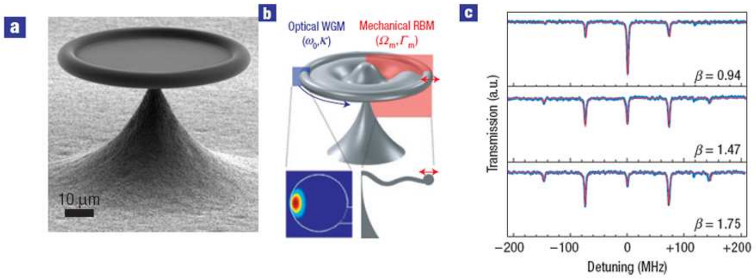

Figure 1: *Radiation pressure cooling of toroidal microcavities in the resolved sideband regime*[2,4].

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Exciton-polariton condensation in semiconductor microcavities

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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

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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

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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

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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.

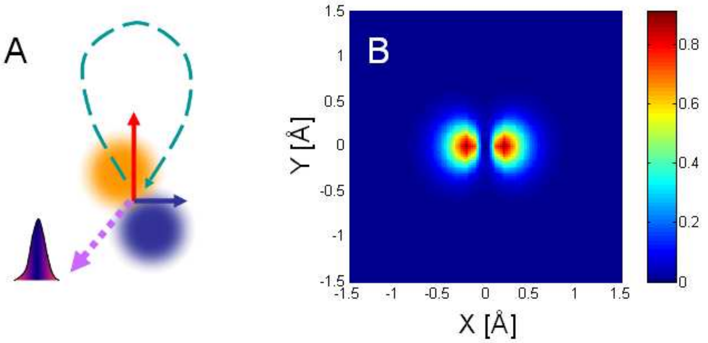

Figure 1: *A. Schematic drawing of attosecond pulse generation with a two color field. The motion of the electron is schematically described by the blue dashed line. The recollision projects the ground state into the optical frequencies of the emitted pulse. B. Retrieved Neon mixed $2p$ orbital.*

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