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

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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)].

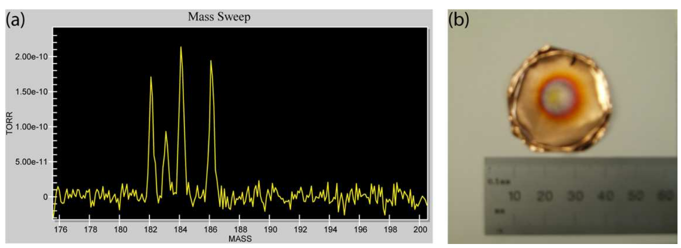

Figure 1: *Tungsten atomic beam diagnostics. (a) Quadrupole mass spectrum of W isotopes evaporated from a filament. (b) Ar + W supersonic beam sputtered onto a copper foil placed* ~ 25 *cm downstream from a* 3 *mm diameter skimmer.*

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].

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Search for the electron’s electric dipole moment with cold ThO molecules

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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

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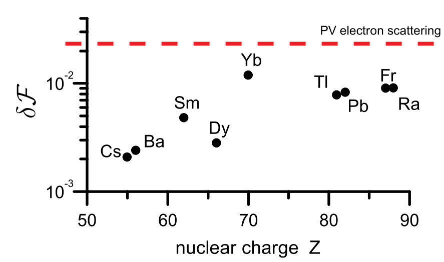
Atomic parity non-conservation (PNC) provides powerful constraints on extensions to the standard model of elementary particles. In such measurements one determines a parity-violating signal $E_{\rm PNC}$, related to the quantity of interest, the weak charge, Q_W, as $E_{\rm PNC} = k_{\rm PNC}\, Q_W$. 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.



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Characterization of an high precision cold atom gyroscope

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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

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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].

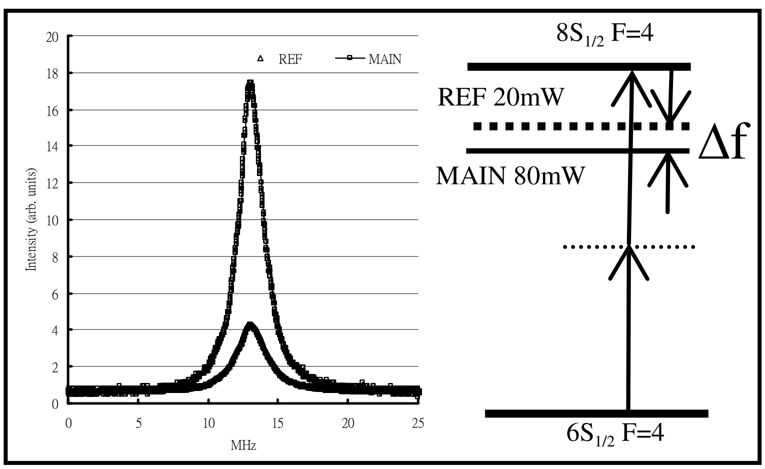

Figure 1: *Left: Violet fluorescence from Cs(7P→6S) in both REF and MAIN cells were monitored by a filtered-PMT simultaneously. Right: The relative energy positions indicate the Cs 6S-8S two-photon transition and light shift for different laser power (not to scale).*

[1]This work was supported by the National Science Council, Taiwan.

Precise Measurement of the Isotope Shift of the Lithium D Lines

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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

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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

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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

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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 $\mathbf{g}$:

$$\Delta E = 2k\frac{\hbar g}{c} \approx k \times 4 \times 10^{-23} \text{ eV} ,$$

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 $\mu\text{Hz}/\sqrt{\text{Hz}}$ 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.

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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 ≈ 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

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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

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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

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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.

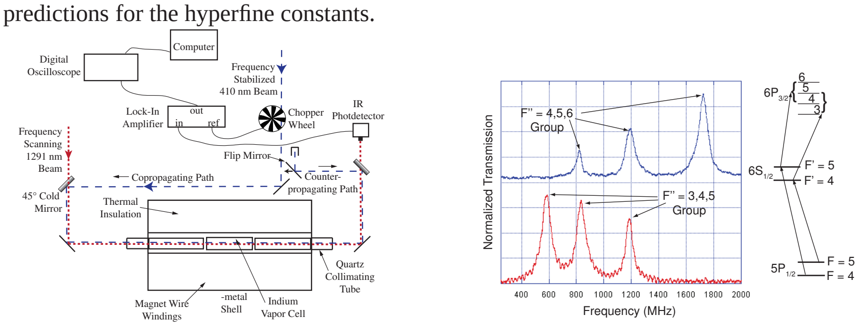

Figure 1: *Sketch of indium spectroscopy setup (left). Hyperfine scans and levels (right).*

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

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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

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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 $| d_e | < 1.6 \times 10^{-27}$ $e \cdot cm$.[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

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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.

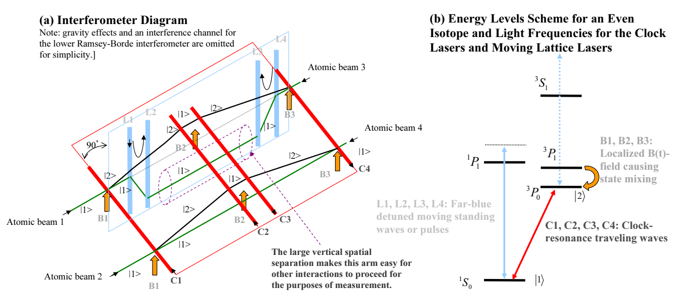

Figure 1: *(color online). An atom interferometer for rotation measurement.*

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News from the Muonic Hydrogen Lamb Shift Experiment

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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

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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

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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.

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Elimination of non-linear Zeeman splitting using AC Stark shifts

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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.

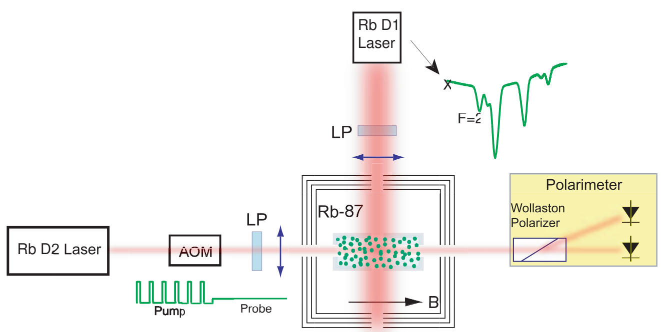

Figure 1: *Apparatus. Light from a Rb D2 laser is used to stroboscopically pump alignment in a Rb-87 paraffin coated cell. Weak cw light from the laser then probes the free induction decay of the optical rotation due to the induced linear dichroism. A Rb D1 laser far detuned from the Rb-87 resonance 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

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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

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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

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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

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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

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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

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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.

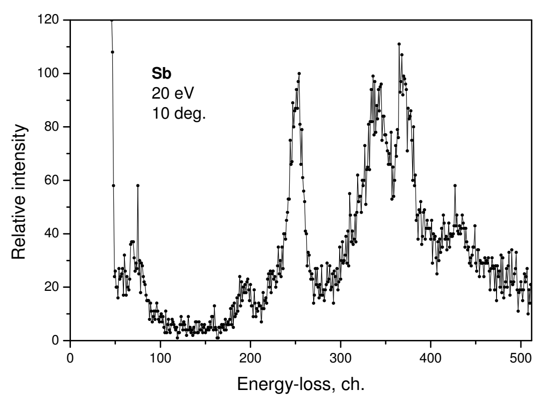

Figure 1: *Energy loss spectrum of antimony vapor obtained by heating of pure crystalline antimony at approximately 900 K.*

[1]B. P. Marinković, V. Pejčev, D. M. Filipović, D. Šević. S. Milisavljević, B. Predojević, Rad. Phys. Chem. 76 (2007) 455.
[2]M. S. Rabasović, V. I. Kelemen, S. D. Tošić, D. Šević, M. M. Dovhanych, V. Pejčev, D. M. Filipović, E. Yu. Remeta, and B. P. Marinković, Phys. Rev. A 77 (2008) accepted; S. D. Tošić et al. NIMB, (2008) submitted.

A radio-frequency assisted d-wave Feshbach resonance in the strong field regime

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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].

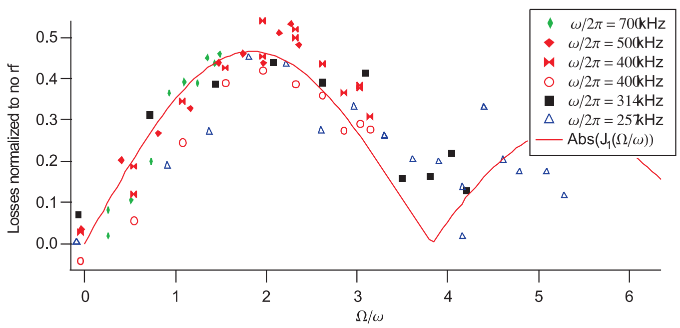

Figure 1: *Losses observed near the Feshbach resonance for different resonant rf frequencies. Irrelevant of ω and Ω, losses only depends on $\frac{\Omega}{\omega}$. We also plot $\left|J_1\left(\frac{\Omega}{\omega}\right)\right|$.*

[1]P. Pillet et al., Phys. Rev. A **36**, 1132 (1987)

An atomic Fresnel biprism interferometer.

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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.

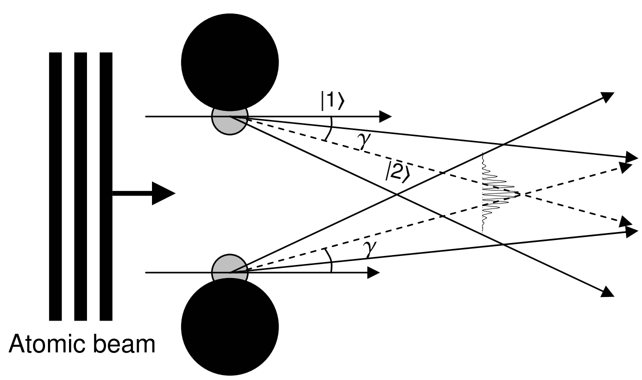

Figure 1: *The atomic Fresnel biprism interferometer principle.* γ *is the angular deviation induced by the passage from the* $|1\rangle$ *to the* $|2\rangle$ *magnetic sub-level.*

[1] J.-C. Karam et al., Europhys. Letter **74**, 36 (2006)
[2] J. Grucker et al., Euro. Phys. J D **47**, 427-431 (2008)

Cold Collision Shift of Magnetic Resonance in Atomic Hydrogen Gas

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We report on an experimental study of magnetic resonance line shifts in cold spin-polarized atomic hydrogen gas (H$\downarrow$). 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$\downarrow$ 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$\downarrow$ 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.

[1] S. Vasilyev, J. Järvinen, A. I. Safonov, and S. Jaakkola, Phys. Rev. A. 69 (2004) 023610.
[2] J. Ahokas, J. Järvinen, and S. Vasiliev, Phys. Rev. Lett. 98 (2007) 043004.
[3] M. J. Jamieson, A. Dalgarno, B. Zygelman, P. S. Krstić, and D. R. Schultz, Phys. Rev. A. 61 (1999) 014701.

Theoretical study of an excitation blockade in ultracold Rydberg gases

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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.

[1] J. Stanojevic and R. Côté, arXiv:0801.2396.
[2] R. Heidemann, U. Raitzsch, V. Bendkowsky, B. Butscher, R. Löw, and T. Pfau, Phys. Rev. Lett. **100** , 033601 (2008).

Towards thermal equilibrium of atomic polariton states

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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.

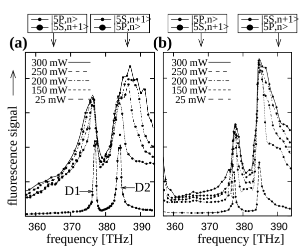

Figure 1: *Fluorescence spectrum of rubidium D-lines at (a) 500 bar argon and (b) 400 bar helium buffer gas pressure for different driving optical beam powers. The relative population of dressed states on the red and blue side of the transition respectively are indicated in the small drawings on the top of the figure.*

[1] See, e.g.: R. Balili et al., Science 316, 1007 (2007)
[2] U. Vogl and M. Weitz, ArXiv:0704.2151 ⟨http://arxiv.org/abs/0704.2151v1⟩

Charge Transfer Between Cold Atoms and Ions

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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

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We measure the inelastic loss rates of the metastable ^{3}P$_2$ and ^{3}P$_0$ 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 ^{3}P$_2$ level and about 1.25×10^{-11} for the ^{3}P$_0$ level. The value of the ^{3}P$_2$ lifetime qualitatively agrees with the theoretical values calculated in Kokoouline et al.[1] and is consistent with measured rates of the ^{3}P$_2$ 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.

[1] V. Kokoouline, R. Santra, and C. Greene, Phys. Rev. Lett. 90, 253201 (2003).
[2] D. Hansen and A. Hemmerich, Phys. Rev. Lett. 96, 073003 (2006).
[3] A. Yamaguchi, S. Uetake, D. Hashimoto, J.M. Doyle, and Y. Takahashi, submitted to Phys. Rev. Lett. (2008); arXiv:0802.0461v1.

Theoretical Investigations on Ion-Atom collision

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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

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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.

[1] D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Cote, and M. D. Lukin, Phys. Rev. Lett. 85, 2208 (2000).
[2] T. A. Johnson, E. Urban, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, and M. Saffman, Phys. Rev. Lett. 100, 113003 (2008).
[3] W. Alt, D. Schrader, S. Kuhr, M. Müller, V. Gomer, and D. Meschede, Phys. Rev. A 67, 033403 (2003).
[4] A. K. Mohapatra, T. R. Jackson, and C. S. Adams, Phys. Rev. Lett. 98, 113003 (2007).

Magnetic trapping and anomalous inelastic collisions in the few-partial-wave regime

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[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.

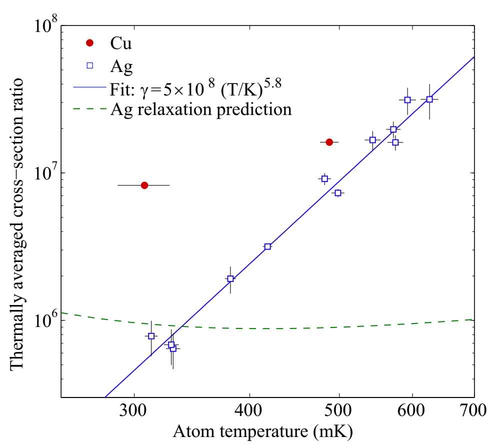

Figure 1: *Ratio γ of elastic to inelastic collision cross-sections vs. temperature for the Cu–^{3}He and Ag–^{3}He systems.*

Coherent Control of Ultracold Collisions with Nonlinear Frequency Chirps on the Nanosecond Timescale

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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.

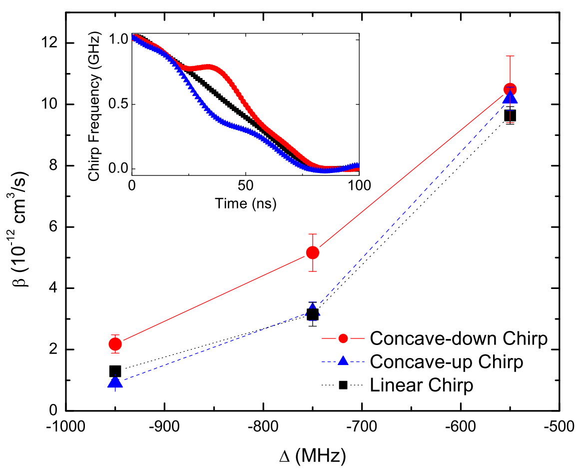

Figure 1: *$\beta(\Delta)$ for negative, nonlinear frequency chirps. The concave-down chirp yields a higher β than linear and concave-up chirps at Δ = -750 MHz. The inset shows the various chirp shapes. The 40 ns FWHM pulses are centered at 40 ns.*

[1] M.J. Wright et al., Phys. Rev. A **75** 051401(R) (2007)

Energy Relaxation in Collisions of Atomic Particles

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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

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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.

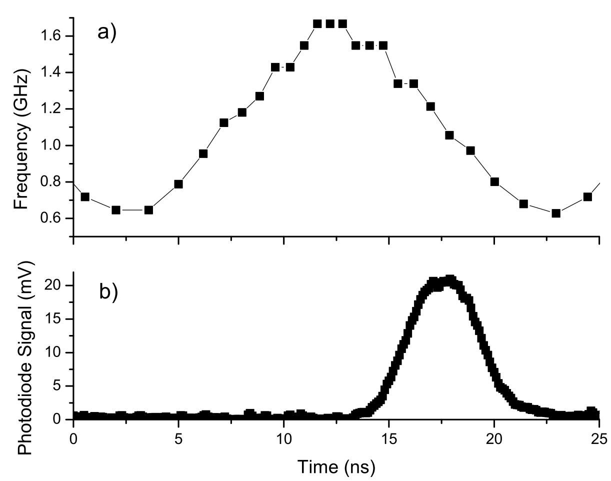

Figure 1: *(a) A 1 GHz linear frequency chirp in 10 ns. (b) The corresponding 4 ns Gaussian pulse selecting out the center of the negative chirp.*

[1]C.E. Rogers III, et. al., J. Opt. Soc. Am. B **24**, 1249-1253 (2007)

Photoassociation spectroscopy of cold metastable neon

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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.

[1] Jones et al. Rev. Mod. Phys. 78, 483-535, 2006
[2] John Weiner et al. Rev. Mod. Phys. 71, 1-85 (1999)
[3] N. Herschbach et al. Phys. Rev. Lett. 84, 1874-1877, 2000
[4] J. Kim et al. Euro. Phys. D, 31, 227-237, 2004

Long-range Wells in Rydberg-Rydberg Potential Curves

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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

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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

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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+} *

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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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Cold Titanium-Helium Collisions

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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)	$k_{3\to2}$ (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 $k_{3\to2}$, 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

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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.

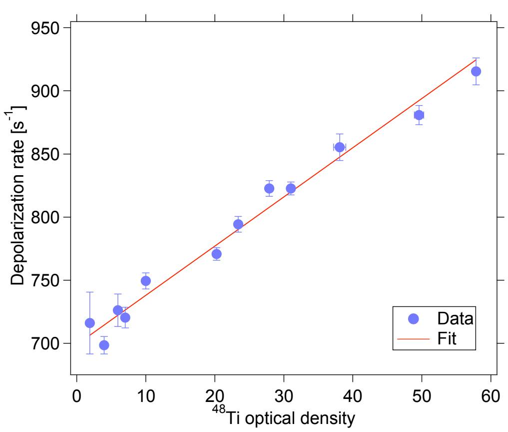

Figure 1: ^{50}Ti depolarization rate as a function of titanium density. (Taken at helium density 7×10^{15} cm^{-3}.) The offset is due to Ti–He m-changing inelastic collisions, the slope is due to Ti–Ti m-changing collisions.

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

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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

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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 $7^{\rm th}$ 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 $k_{\rm perp}$ of the atom's wave vector is decreased from 0.3 to less than 0.02 nm^{-1}. A kink at $k_{\rm perp} \simeq 0.12$ nm^{-1} separates a slow simple exponential decrease at larger $k_{\rm perp}$ from a steep decrease at smaller $k_{\rm perp}$. 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.

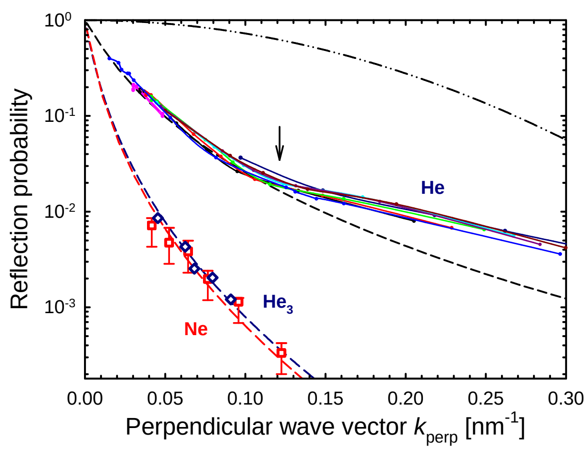

Figure 1: *Coherent reflection probability for He, He_3, and Ne. The slope of the observed data (points and solid lines) cannot be explained by a classical surface-reflection model (dash-dotted line), but, for small $k_{\rm perp}$, it is well reproduced by a 1-dimensional quantum-reflection model (dashed lines).*

Spinor Dynamics in an Antiferromagnetic Condensate

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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.

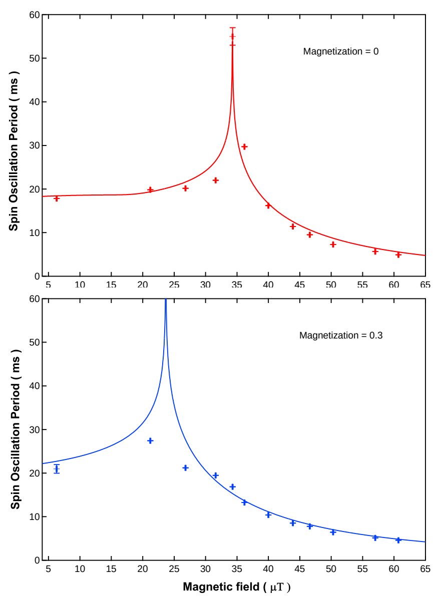

Figure 1: *Period of spin oscillations as a function of applied magnetic field when magnetization is equal to 0 (above) and 0.3 (below). The solid lines and dots are theoretical predictions and experimental data, respectively.*

Investigation of the energy distribution and cooling of a single atom in an optical tweezer

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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 $w = 1.03 \pm 0.01\ \mu\mathrm{m}$ 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 $33\ \mu$K 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

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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

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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

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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.

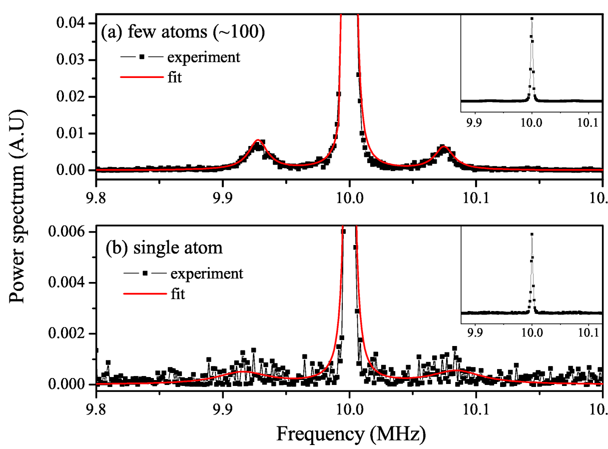

Figure 1: *Resonance fluorescence spectrum of (a) a few atoms and (b) a single atom measured by the photon-counting second-order correlation spectroscopy.*

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Cavity cooling of ^{88}Sr$^+$

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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

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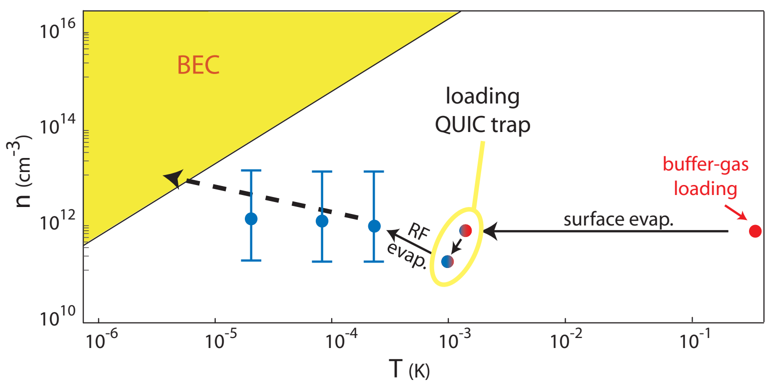
We report recent progress towards producing a BEC of metastable helium ($^4He^*$) using buffer gas cooling. 10^{11} $^4He^*$ atoms are produced via RF-discharge and magnetically trapped at an initial temperature of 400 mK in an anit-helmholtz quadrupole field. These atoms are evaporatively cooled to 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

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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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[2] B.J. Claessens *et al*, Phys. Rev. Lett. 95, 164801 (2005)
[3] B.J. Claessens *et al*, Phys. Plasmas 14, 093101 (2007)
[4] G. Taban *et al*, Phys. Rev. STAB 11, 050102-1, (2008)

Solid-state laser source at 589 nm for laser cooling of Sodium

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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].

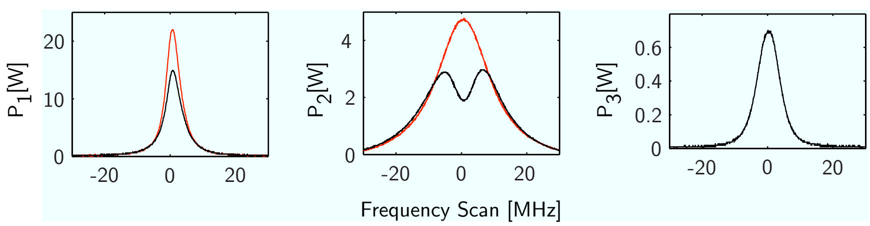

Figure 1: *Intra-cavity SFG : Lasers 1 (1064 nm) and 2 (1319 nm) are enhanced in an optical cavity. When simultaneously resonant they produce a laser noted 3 at 589 nm. Powers for the three lasers are plotted while the length of the cavity is scanned. The depletion of lasers 1 and 2 changes the shape 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.

[1] Z. Hadzibabic *et al.*, Phys. Rev. Lett. 88, 160401 (2002)

Superconducting atom-chip for groundstate and Rydberg atoms

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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.

[1]U. Hohenester et al., Phys. Rev. **A 76**, 033618 (2007)
[2]C. Roux et al., in preparation
[3]P. Hyafil et al., PRL **93**, 103001 (2004)
[4]T. Nirrengarten et al., PRL **97**, 200405 (2006)
[5]C. Roux et al., EPL **81**, 56004 (2008)
[6]M.D. Lukin et al., PRL **87**, 037901 (2001)

Imaging magnetic fields using velocity selective resonances in cold atom clouds

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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.

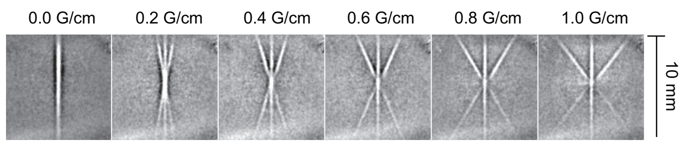

Figure 1: *Images of the expanded atom cloud, after background subtraction, for several magnetic field gradient values.*

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

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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*

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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*

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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.

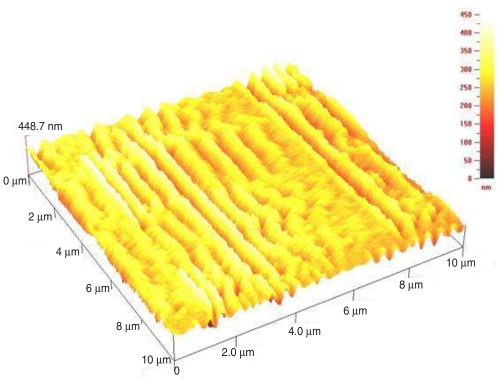

Figure 1: *An AFM scan of an etched wafer whose lines are spaced by ≈530 nm. Within the calibration accuracy of the AFM, this is $\lambda/2$ of the 1083 nm wavelength of the $2^3S_1 \rightarrow 2^3P_2$ transition. The wiggles are artifacts of the AFM scan.*

* 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

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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

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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

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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

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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.

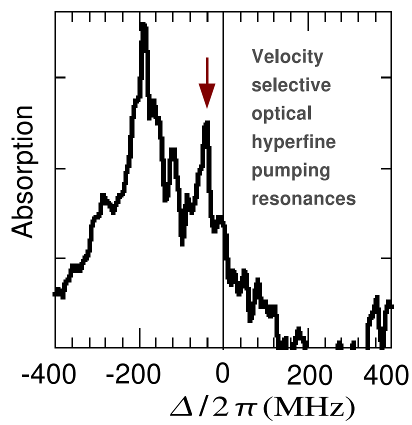

Figure 1: *the arrow marks the hyperfine resonance at* $\Delta = -6\Gamma$

Trapped-Atom Cooling Beyond The Lamb-Dicke Limit Using Electromagnetically Induced Transparency

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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 and 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.

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[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

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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

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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

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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].

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Comparison of laser cooling and trapping of even and odd calcium isotopes

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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.

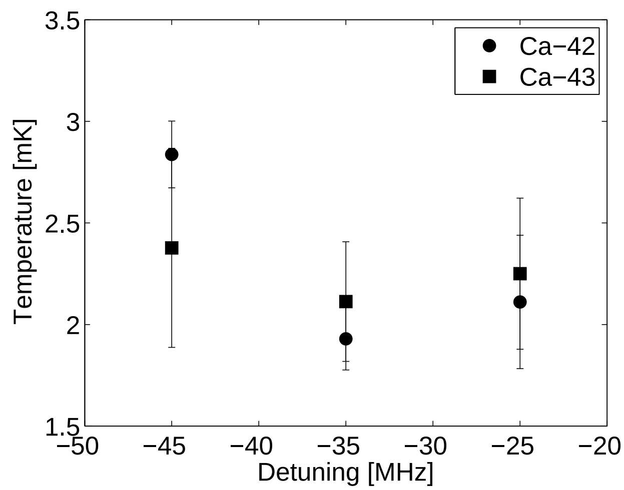

Figure 1: *Results of temperature measurements of ^{43}Ca and ^{42}Ca in a MOT at low ($s_0 = 0.1$) laser intensity.*

[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

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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 $5\ \mathrm{eV}$ are routinely produced with an rms energy spread as low as $0.02\ \mathrm{eV}$. This proves the feasibility of this new ion source concept.

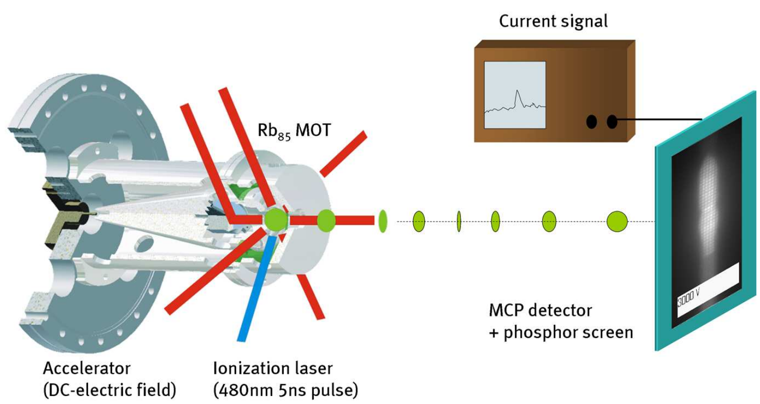

Figure 1: *A schematic overview of the experimental setup. Laser cooled and trapped Rubidium atoms are pulsed ionized and accelerated towards a detector.*

[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

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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.

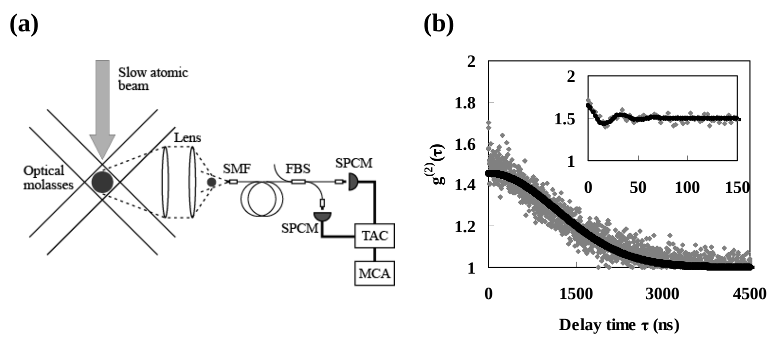

Figure 1: *(a) Experimental setup. (b) Intensity correlation function with -22 MHz-detuned cooling beams.*

Towards a Li-Rb Ring Interferometer

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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.

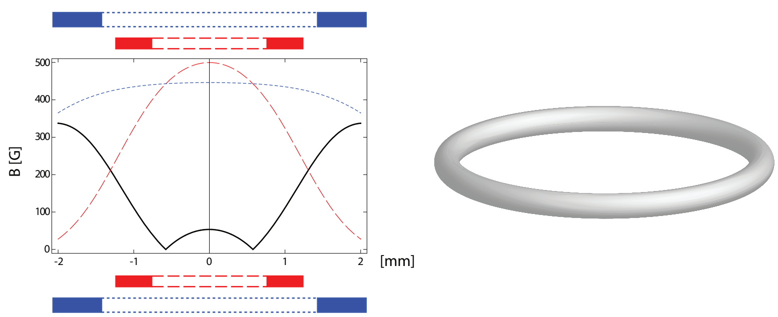

Figure 1: *The magnetic ring trap is generated by the field of a pair of curvature coils (dashed), subtracting a homogenous bias by a pair of antibias coils (dotted). The annulus shaped magnetic zero is transformed in a time-orbiting manner in a biased harmonic potential. The diameter of the ring trap 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.

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[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

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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].

[1]M.-O. Mewes, M. R. Andrews, D. M. Kurn, D. S. Durfee, C. G. Townsend, and W. Ketterle, Phys. Rev. Lett. **78**, 582 (1997)
[2]N. V. Vitanov, and K.-A. Suominen, Phys. Rev. A **56**, R4377 (1997)
[3]E. Majorana, Nuovo Cimento **9**, 43 (1932); F. Bloch, and I. I. Rabi, Rev. Mod. Phys. **17**, 237 (1945)
[4]H. Schmaljohann, M. Erhard, J. Kronjäger, M. Kottke, S. van Staa, L. Cacciapuoti, J. J. Arlt, K. Bongs, and K. Sengstock, Phys. Rev. Lett. **92**, 040402 (2004)

Trapping hydrogen atoms in a neon-gas matrix: A theoretical simulation

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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

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[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.

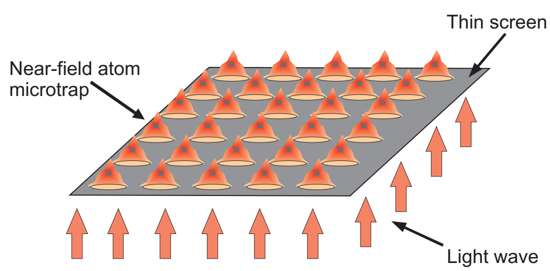

Figure 1: *Schematic of an atom microtrap array.*

[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

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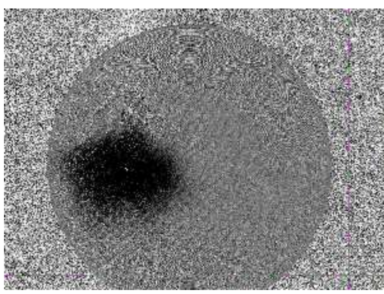
Department of Physics, Seoul National University, Seoul, Korea

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.



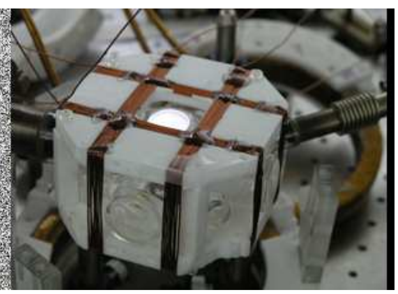


Figure 1: *Absorption image of Trapped Rb^{87} atoms(left).*

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

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[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

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[2]*CREST, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan*
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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.

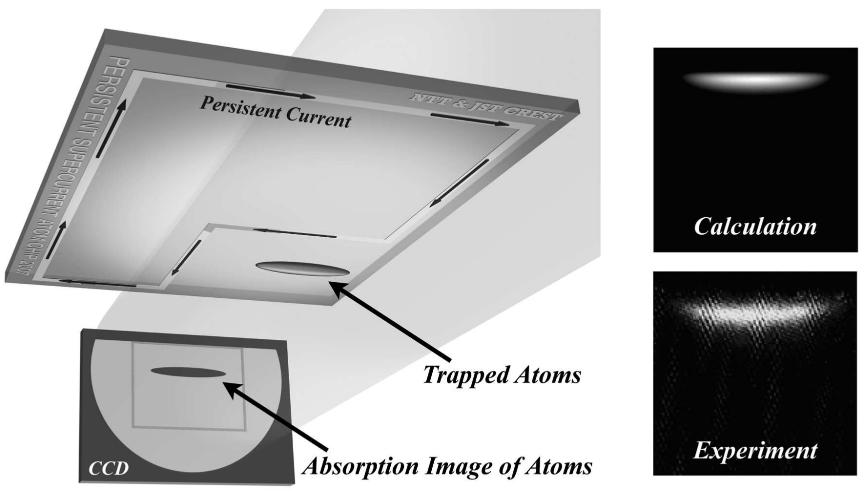

Figure 1: *(left) Image of the experiment. (right) Absorption image of the trapped atoms and the calculated potential shape.*

[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

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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

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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 10^6atoms are trapped in both U-traps. This will provide an excellent physical base for much further researches.

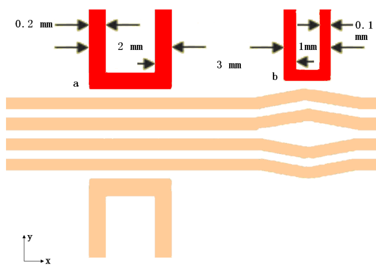

Figure 1: *Diagram of our atom chip, a, b are two U-shape wires.*

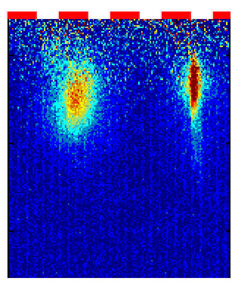

Figure 2: *Fluorescence picture of the double U-type MOT.*

[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)
[4]J. Hu, J. Yin, and J. Hu, "Double-well surface magneto-optical traps for neutral atoms in a vapor cell", J. Opt. Soc. Am. B **22**, 937(2005)

Laser Cooling and Trapping of Barium

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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 (^3P and ^3D) [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 ^3D-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

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[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].

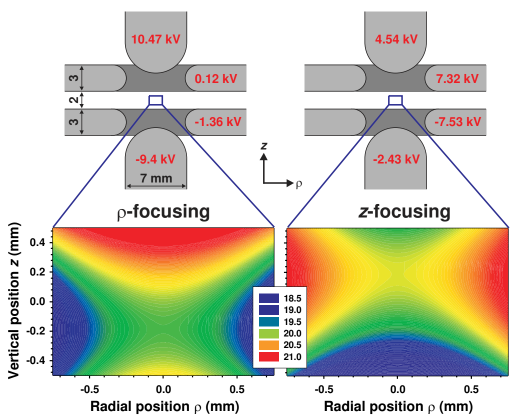

Figure 1: *The cylindrically symmetric AC electric trap consists of two ring and two end-cap electrodes. Dynamic confinement is achieved by switching between two sets of high voltages applied to the electrodes. The color scale marks the field strength in kV/cm.*

[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

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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).

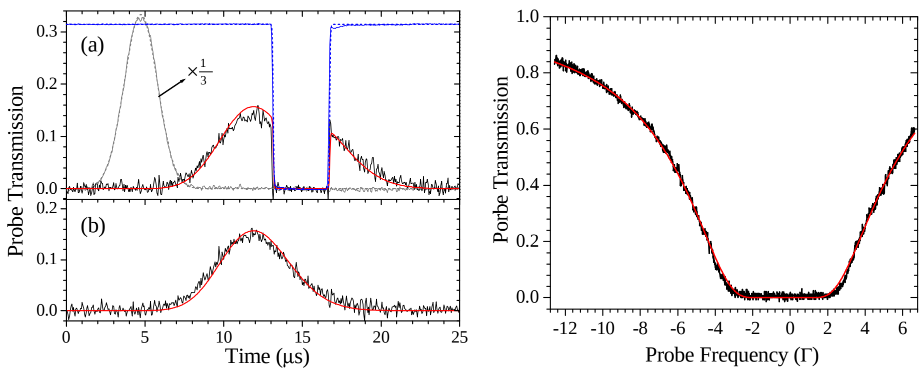

FIG. 1 FIG. 2

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

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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

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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].

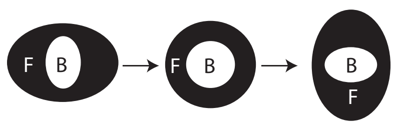

Figure 1: *Out-of-phase collective excitations of trapped phase-segregated Bose-Fermi gases. The trap consists of a bosonic (B) core and a surrounding fermionic (F) shell which move out-of-phase.*

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BEC as a Tool for Quantum Measurement

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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

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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.

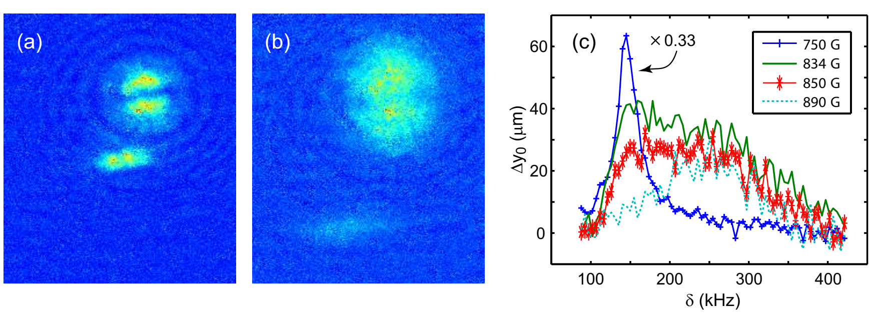

Figure 1: *Bragg scattering of (a) molecules from a molecular BEC and (b) atoms from a highly degenerate Fermi gas, at 730 G and 870 G, respectively. The field of view for both images is 650 μm by 880 μm. (c) Bragg spectra of trapped gases at various magnetic fields across the 834 G Feshbach resonance.*

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Bose-Fermi Mixtures on an Atom Chip

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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.

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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.

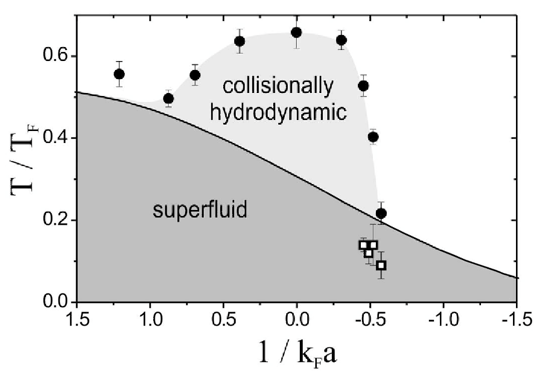

Figure 1: *Phase diagram for the scissors mode showing a nonsuperfluid hydrodynamic region (filled circles). The open squares correspond to an unexpected feature in the damping. The solid line shows a theoretical curve for the phase transition to superfluidity*[5].

[1]A. Altmeyer et al., Phys. Rev. A **76**, 033610 (2007).
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Using photoemission spectroscopy to probe a strongly interacting Fermi gas

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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

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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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[2]J. Kinast *et al*., SCIENCE 307, 1296 (2005)

p-wave Feshbach Molecules of ^{6}Li$_2$

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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

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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

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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

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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

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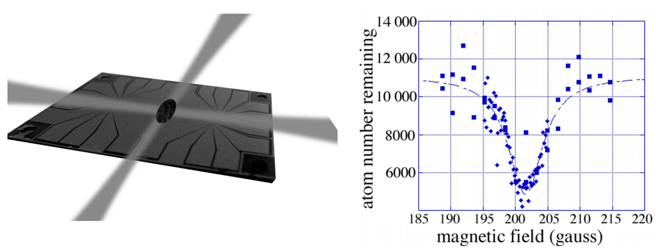
Superfluidity and magnetism are two phenomena which arise in condensed matter physics due to interactions between electrons. In systems of strongly interacting neutral fermions, superfluidity has been demonstrated in the regime of attractive interactions[1,2,3] and magnetism has been predicted in the 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

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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

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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.

[1] B. Deh, C. Marzok, C. Zimmermann and Ph.W. Courteille, Phys. Rev. A **77**, 010701(R) (2008)

[2] C. Marzok, B. Deh, S. Slama, C. Zimmermann and Ph.W. Courteille, submitted to Phys. Rev. Lett., preprint: arXiv/cond-mat/0804.0532

[3] H.P. Büchler, P. Zoller, and W. Zwerger, Phys. Rev. Lett. **93**, 080401 (2004)

BEC-BCS Crossover in ultracold ^{6}Li Fermi gas : a new experimental setup

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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].

[1] Proceedings of the International School of Physics "Enrico Fermi", Course CLXIV, Varenna, edited by M. Inguscio, W. Ketterle, and C. Salomon, IOS Press, Amsterdam (2008)

[2] L. Tarruell, M. Teichmann, J. McKeever, T. Bourdel, J. Cubizolles, L. Khaykovitch, J. Zhang, N. Navon, F. Chevy, C. Salomon, Expansion of an ultra-cold lithium gas in the BEC-BCS crossover, *Proceedings of the 2006 Enrico Fermi summer school on Fermi gases* (2008)

[3] This work is supported by ANR Fabiola and the IFRAF Institute. Laboratoire Kastler-Brossel is associated with CNRS and Université Pierre et Marie Curie.

Population Imbalanced Two-component Fermi Superfluidity inside Box-shape Trap: Self-consistent Calculations of $T = 0$ BdG Equation

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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.

[1] G. Sarma, J. Phys. Chem. Solids **24**, 1029 (1963).

[2] W. V. Liu and F. Wilczek, Phys. Rev. Lett. **90**, 047002 (2003).

[3] P. Fulde and R. A. Ferrell, Phys. Rev. **135** A550 (1964); A.I. Larkin and Y.N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **47**, 1136 (1964) [Sov. Phys. JETP, **20**, 762 (1965)].

[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

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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.

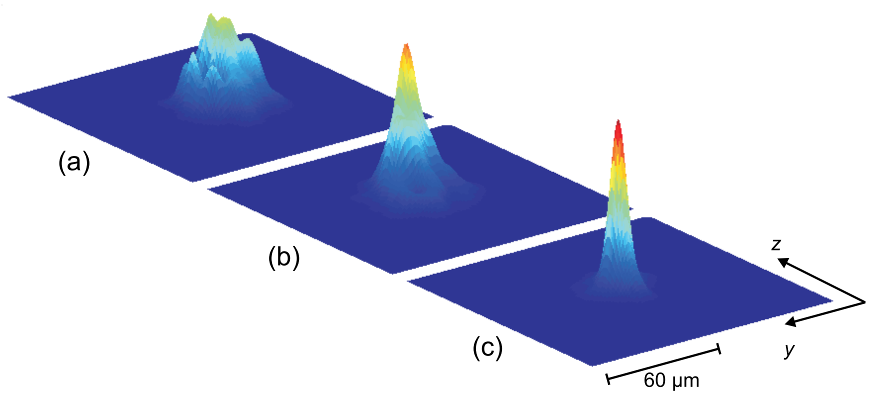

Figure 1: *Simulated density profiles of a two-component ^{6}Li gas undergoing evaporative cooling with strong interactions.*

[1]S. Giorgini, L. P. Pitaevskii and S. Stringari, arXiv:0706.3360v1 (2007)
[2]M. J. Wright *et al.*, Phys. Rev. Lett. **99**, 150403 (2007)
[3]L. Tarruell *et al.*, arXiv:0701181v1 (2007)

Towards a Finite Ensemble of Ultracold Fermions

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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

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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

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[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)$\mathrm{T_F}$. 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

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[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.

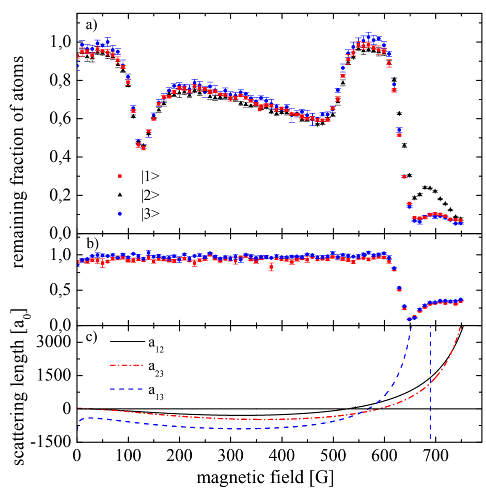

Figure 1: *a) Fraction of atoms remaining in the trap after holding the three-state mixture for 250 ms vs. magnetic field. b) Same measurement for a two-state mixture. Up to the region of the two-body Feshbach resonance the mixture is stable. c) Two-body scattering lengths for all particle combinations.*

[1] arXiv:0806.0587v1

Quadrupole Oscillation in the Bose-Fermi Mixtures in the Time-Dependent Approach

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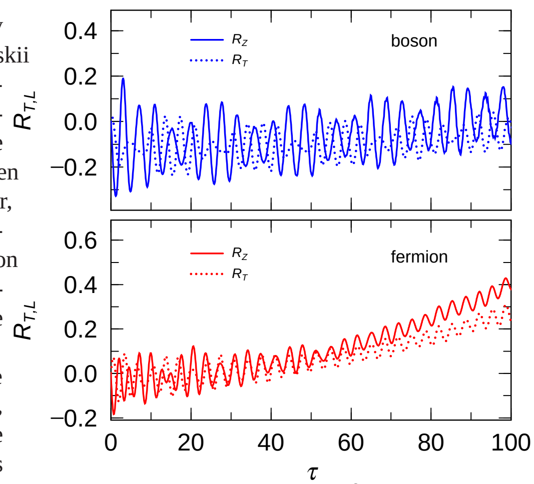
Over the last several years, there have been significant progresses in the production of ultracold gases. degenerate atomic Fermi gases. In particular the Bose-Fermi (BF) mixing gases attract physical interest as a typical example in which particles obeying different statistics are intermingled. The 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 monople 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.

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[2] T. Maruyama and G.F. Bertsch, Phys. Rev. **A**, in press

Resolved-sideband cooling of a micromechanical oscillator

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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.

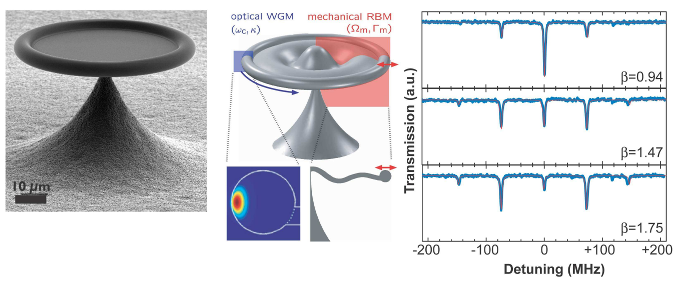

Figure 1: *Optomechanical coupling and resolved-sideband cooling. Electron micrograph (left) of toroidal silica microresonator used for cooling, supporting whispering-gallery modes in the toroid's rim and the mechanical radial breathing mode (center). The excited mechanical mode gives rise to optical 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

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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.

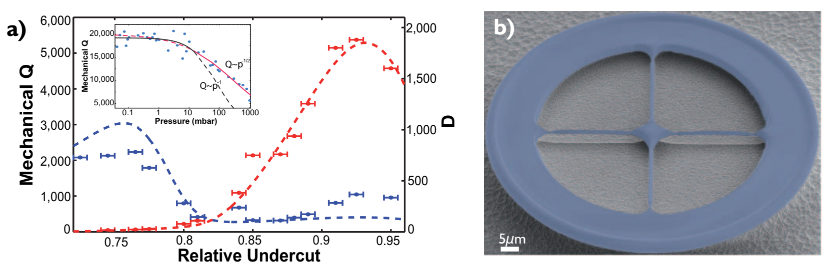

Figure 1: *Understanding and optimizing mechanical dissipation in silica microtoroids. (a) Measured quality factor (points) and simulated D-parameter (dashed lines) as a function of the undercut of the silica toroid. (b) Electron micrograph of an optimized device in which the toroid is supported by narrow 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]

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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.

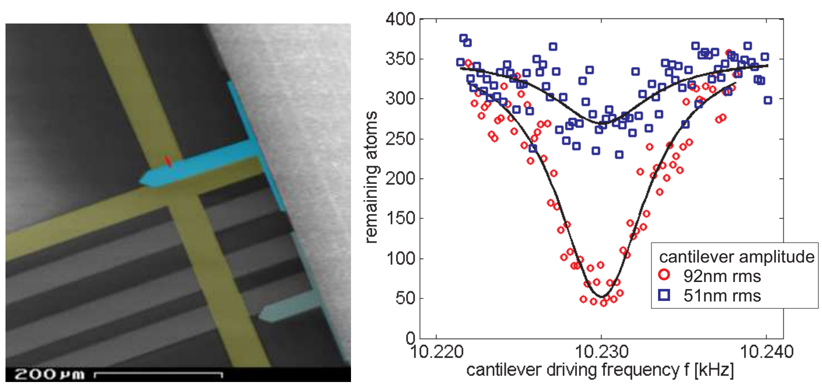

Figure 1: *Left: SEM picture of the AFM cantilever on a chip with gold wires for magnetic trapping. Right: Remaining atom number after* 7 *ms holding time at* 800 *nm distance from the cantilever surface for varying cantilever driving frequency.*

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

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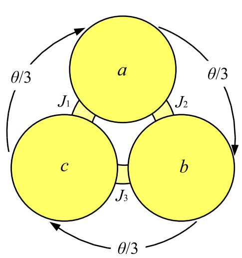
Dilute gases of ultra-cold atoms provide an ideal quantum-many body system for studying macroscopic quantum phenomena. They can be trapped and manipulated using optical and magnetic fields and their interactions are well understood. This means that they can be modelled theoretically starting from the 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.



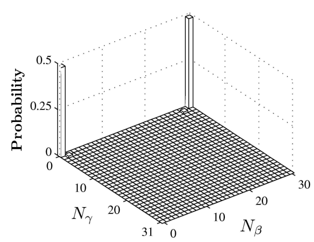


Figure 1: *LEFT: System for creating superpositions of flow. A phase, ϕ, can be applied around the loop, atoms can interact on a site and tunnel between sites with strength J_i. RIGHT: Figure shows a superposition of states $|30,0,0\rangle_{\alpha\beta\gamma}$ and $|0,30,0\rangle_{\alpha\beta\gamma}$.*

[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

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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

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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

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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 $\text{TEM}_{20,11,02}$ 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.

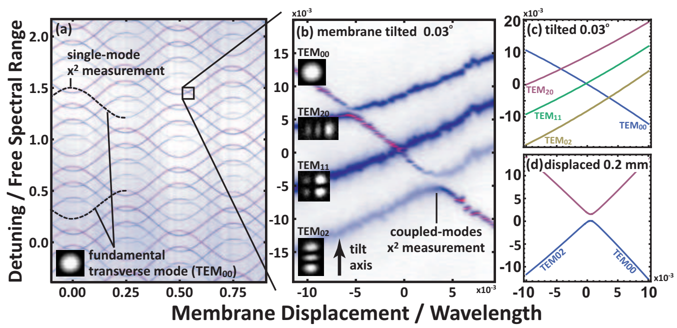

Figure 1: *(a) Cavity transmission coupled to many modes. (b) Singlet/triplet crossing. (c) Model, showing effect of tilt on triplet degeneracy. (d) Degenerate model.*

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

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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.

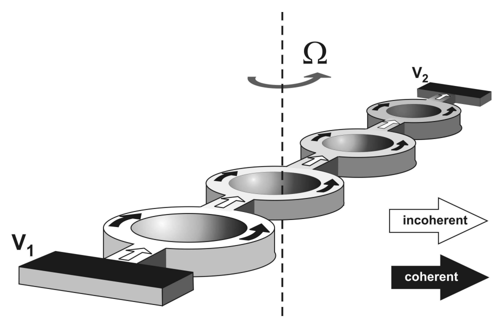

Figure 1: *An array of ring interferometers connected in series with a bias voltage $V_1 - V_2$. The electron beam is split as it enters the ring and a rotation, Ω, induces a path difference between the two beams resulting in phase shift proportional to Ω. The interference is measured in the total conductance of the array.*

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Cooling and detecting nanomechanical motion with a microwave cavity

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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 back-action technique to cool a mechanical mode entirely to its quantum ground state with microwaves.[2]

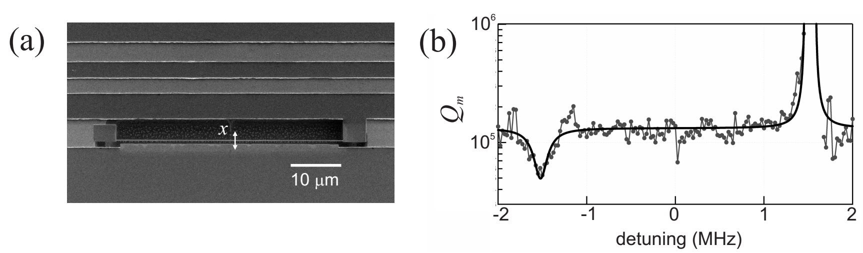

Figure 1: *(a) A nanomechanical beam embedded in a transmission-line microwave cavity. The beam motion in x capacitively couples to the cavity resonance frequency. (b) Effect of microwave radiation pressure on the mechanical quality factor as a function of microwave carrier detuning from the cavity resonance.*

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Observation of Bogoliubov excitations in exciton-polariton condensates

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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.

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‘Trapped Rainbow’ in Graphene

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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.

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