Classical Theory of Mirror-Mediated Cooling

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We have calculated, using a classical approach, the frictional force on a polarisable particle which is illuminated with far-detuned light and coupled, via the dipole force, to its reflection.

Established methods for cooling atoms with light require a closed optical transition; they rely on the atom to provide the necessary dissipation. A new breed of techniques is emerging in which particles and light are coupled using the dipole rather than the scattering force; for these, it is the light, not the particle, which provides dissipation. Examples include cavity-mediated cooling[1,2] and the proposed mirror-mediated cooling[3]. For these techniques, the only property required of the particle is that it be polarisable; specifically, there is no need for a closed optical transition. Potentially, we can achieve direct, optical cooling of molecules and even much larger structures, such as micro-cantilevers[4].

In cavity-mediated cooling, a particle is placed at the focus of an optical cavity which is pumped with light sufficiently detuned from any absorption feature that dissipation can be neglected. The standing wave in the cavity acts as an optical lattice and exerts a force on the particle; simultaneously, the position of the particle relative to this standing wave influences the phase-delay of light crossing the cavity. Hence, the particle affects the field and the field affects the particle. Similarly, in mirror-mediated cooling, a particle is placed in front of a mirror and is illuminated by far off-resonant laser light. Light passing the particle is perturbed by it, and this perturbed field is reflected back onto the particle; hence, the particle is coupled to a time-delayed image of itself. This retarded interaction is common to both mirror- and cavity-mediated cooling, and is the essential ingredient for cooling via the dipole force.

These techniques are often described using the same tools, such as fully-quantum treatments or the semi-classical approximation, as are used for the more traditional schemes, such as Doppler cooling. However, the dipole interaction is, for our purposes, adequately described by a classical field interacting with a classically polarisable particle. Hence, a fully classical approach is appropriate, and is complimentary to quantum mechanical models. For example, using a fully classical model we can readily treat three dimensions and tensor propagators; by contrast, mirror-mediated cooling has thus far been described using a generalisation of transfer matrices[5], and it is unclear whether this approach can be extended beyond one dimension.

We begin with a moving polarisable particle in front of a mirror and we ask how long it takes a perturbation in the field, caused by this particle, to return to this particle; we find that even this seemingly simple question must be treated with care. Armed with our solution, we ask what field we should expect at the particle when we include the propagated perturbation to the field. Our approach is general: we apply it to one-dimension for comparison with the result obtained via the transfer matrices, and then, using the tensor propagator, we find a full-three dimensional expression for an infinite plane mirror. Finally, we discuss the application of this result to large polarisable particles, such as micron-scale glass beads, and to arbitrarily curved mirror surfaces and cavities.

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Quantum State Preparation using Adiabatic Techniques

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Controlling the dynamics of quantum systems with high fidelities while not compromising fast time scales is one of the most important criteria that ultimately any realistic quantum information processor must fulfill. This usually requires excellent time-dependent control over several experimental parameters, making it technically challenging. For not-completely time-critical applications, however, alternative adiabatic techniques can be used that allow to transfer time-dependent control into fixed system parameters.

Here we investigate techniques for state preparation of single atoms in systems of spatially separated-trapping potentials. For such systems it was recently shown that an analogue to the celebrated three-level STIRAP technique in optics can be constructed, allowing for high fidelity atomic transport as well as EIT and CPT. As spatial atom-optical systems contain various additional degrees of freedom as compared to optical systems (e.g. multiple spatial dimensions, particle interactions, quantum statistics, etc.), they hold a large promise for developing new and exciting techniques based on dark states.

Several applications of such states have been discussed in the literature recently, however suggestions for experimental implementation are currently very sparse. This is due to the fact that the resonance criterium for the asymptotic trapping potentials, which has to be fulfilled at any point during the process, is usually violated once the potentials start to overlap asymmetrically. Here we present a detailed investigation into two experimentally realistic systems in which this can be overcome by shaping the traps in a time dependent manner: atomic waveguides on atom chips and atomic rf-potentials.

Magneto-optical trapping of ^{41}K and ultracold collisions with ^{85}Rb

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We designed and constructed series of systems to create two-species of MOTs (magneto-optical trapping): ^{85}Rb and ^{41}K, and detect the fluorescence radiated from these ultracold atomic gas. Since the biggest long range interaction between ^{85}Rb and ^{41}K among the isotopes of potassium and rubidium, we are interesting of their collision reactions.

In order to create MOTs, we trap atomic gas of ^{85}Rb and ^{41}K by Doppler cooling and cool atoms under milli-Kelvin by focusing six red detuned laser beams on the center of chamber, then add two anti-Helmholtz coils to produce a potential well for trapping the two species of atoms. At last, we use a repumping laser to excite atoms back into the cooling cycle.

Our cooling beams are from three diode lasers, two for rubidium (780 nm) and the other is for potassium (766 nm). We lock the frequencies on atomic resonances by saturation absorption spectroscopy.

Due to the unresolved energy level of potassium, we use the method of injection lock to produce the frequency we want for repumping beam, and wish to get more total power of cooling beams, and a better stability of power after passing through the tapped amplifier.

After creating MOT by Doppler cooling, we use polarization gradient cooling on rubidium and far-off resonance dipole trap to get a high-phase-space density gas which means a lower temperature and higher atomic density gas.

We apply a homemade Ti:sapphire laser on ultracold atoms in MOTs to induce a atom-light interaction and produce a bound state of Potassium atom and Rubidium atom.

The research on ultracold molecule has the potential applications in quantum computing, ultracold quantum chemistry, and sub-nanoscale precision measurement.

Microscopic Atom Trap Arrays

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Microscopic atom trap arrays permit the miniaturisation of cold atom experiments and provide large numbers of individually addressable atom traps in a regular formation. They are therefore a promising environment for quantum simulation and the experimental realisation of quantum information processing[1]. We are developing a versatile and cost effective method for producing such arrays, in which the trap spacing can be set anywhere between 100μm and 20nm. This enables a movement away from the wavelength scale spacing required for optical lattice based systems.

Regular arrays of concave micro-mirrors are fabricated via a templated electrodeposition process[2]. The use of a novel geometry[3] has allowed a magneto-optical trap (MOT) for ^{85}Rb atoms to be formed a few mm below one such structure. The array contains ∼230 concave gold mirrors; each has a focal length of 25μm and brings the light from its projected area of 3,300μm^2 to a focus with a waist of 6μm.

It is intended to illuminate these mirrors at normal incidence with an 808nm laser, thus forming an array of dipole traps at their foci. This will be followed by magnetic transfer of the MOT cloud to the region of the dipole traps. To allow loading from the atom cloud, a 2D-MOT will be created in the plane of the dipole trap array. This should result in the capture of ∼100 atoms per trap site. We expect trap depths in the mK range and lifetimes of several seconds. A multi-level, low-background imaging system (based on the 420nm transition of ^{85}Rb atoms) will be used, eliminating scattering from the gold surface as a source of noise[3]. It should be possible to detect single trapped atoms on timescales of ∼5μs with a PMT, or ∼2ms with an EMCCD camera.

In the longer term, fabrication techniques that may allow the production of microscopic MOT arrays are being considered. The structures required for these would permit simultaneous formation of dipole traps and MOTs, with coincident trap centres. As such, the MOT array could be used to facilitate the loading of the dipole traps, and the whole system may provide a convenient framework for the sympathetic cooling of molecules.

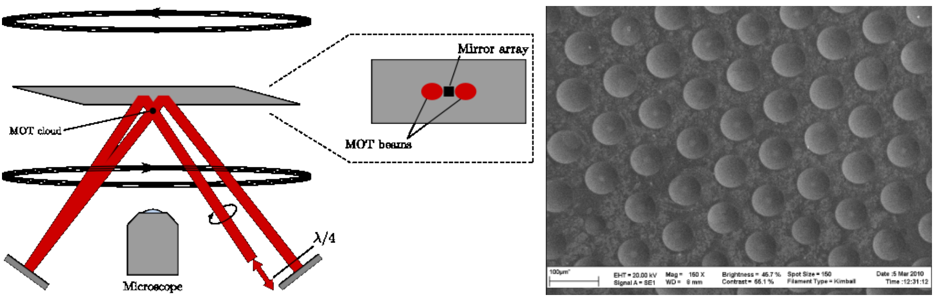

Figure 1: *[left] arrangement used to form a MOT close to the micro-mirror array (another trapping beam is applied perpendicular to the plane of the diagram); [right] SEM image of part of the array.*

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Ultra Cold source temperature measurement with a time-dependent electric field

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The ultra-cold ion source (UCIS) is based on creating very cold ion beams (T $<$ 1 mK) by near-threshold photo-ionization of a laser-cooled and trapped atomic gas. The UCIS has the potential of producing ion beams with a brightness and current comparable to the liquid-metal ion source (LMIS)[1], which is the current state-of-art for focused ion beam (FIB) technology. We have already shown[2] that the UCIS can provide much lower energy spread than LMIS, and may therefore offer a route toward 1-nm ion beam milling[3]. In our experiment, ^{85}Rb atoms are confined in a magneto optical trap (MOT) built directly inside an accelerator structure. A spherical portion of the atom cloud is ionized and the ions are accelerated by a pulsed electric field (see Fig. 1). The ultra low temperature of the source permits collimated bunches to be created at low energy (down to about 14 eV), which allows using time-dependent fields for accelerating and focusing. The duration of the accelerating electric field pulse (typically a few μs) can be tuned in order to cancel the negative lens effect due to the geometry of the accelerator structure. The effect can even be reversed so that a focusing lens is created. Focusing properties of this lens-system have been simulated and experimentally studied for different parameters, such as duration of the pulse, amplitude of the electric field, etc. A source temperature of about 1 mK has been measured.

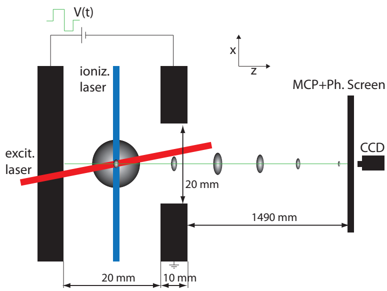

Figure 1: *Scheme of the experimental setup (not to scale) in the x-z plane. The ionization laser (blue) and the excitation laser (red) select a portion of the atomic cloud cooled and trapped in the accelerator. The bunched ions are accelerated using a time-dependent potential $V(t)$ and after a flight distance of 1.51 m they reach a MCP detector with a phosphor screen. The images are captured by a CCD camera.*

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Vortex Based Superconducting Atom Chip

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We store and control ultra-cold atoms in a new type of trap using magnetic fields of vortices in a high temperature superconducting micro-structure. This is the first time ultra-cold atoms have been trapped in the field of magnetic flux quanta. We generate the attractive trapping potential for the atoms by combining the magnetic field of a superconductor in the remanent state with external homogeneous magnetic fields. We show the control of crucial atom trap characteristics such as an efficient intrinsic loading mechanism, spatial positioning of the trapped atoms and the vortex density in the superconductor. The measured trap characteristics are in good agreement with our numerical simulations.

Source Temperature Measurements of an Ultracold Electron Source

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We report on the development of ultracold electron beams. These beams are created in three steps, see Fig. 1. First, Rb atoms are cooled and trapped with laser cooling techniques. Then, a part of the cloud of trapped atoms is photoionized near the ionization threshold. Finally, the electrons are extracted and accelerated by a DC electric field. An alternative way of making ultracold electron beams is by exciting trapped atoms to Rydberg atoms, and subsequently field-ionizing these.

The electron beams that are created from this source will be used to perform single-shot, ultrafast electron diffraction (UED) experiments on crystals of macromolecules, such as proteins. This opens the possibility to study the dynamics of non-equilibrium structures with both spatial and temporal resolution at the atomic level (i.e. 1 nm and 100 fs).

To ensure high quality diffraction data, the electron beams should be sufficiently coherent, with a transverse coherence length of at least a few lattice spacings of the crystal under investigation. For protein crystals the lattice spacing is typically a few nm. Because of the very low temperature of the source, which is of the orders of Kelvins, the coherence length requirement is amply fulfilled.

We will present measurements of the source temperature, which can be as low as 10 K. Furthermore plans for the future setup are outlined, which will enable single-shot UED on macromolecular crystals.

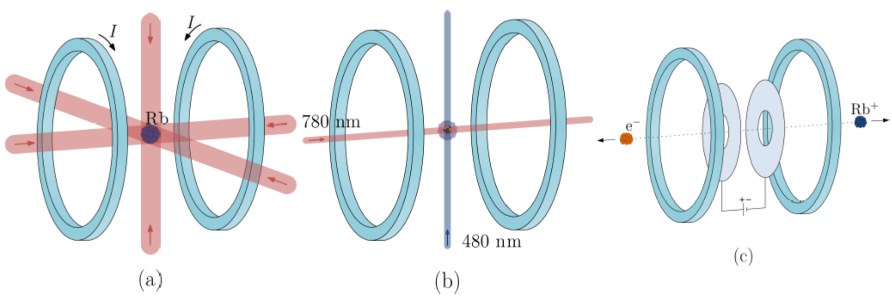

Figure 1: *The creation of ultracold electron beams in three steps: (a) Laser cooling and trapping of Rb atoms. (b) Near-threshold photoionization. (c) Acceleration by a DC electric field.*

Mirror-mediated cooling of atoms, molecules and particles

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Single mirrors, both micro-fabricated and macroscopic, offer a variety of geometries for the manipulation of atoms and molecules. We describe here a new mechanism based upon the retarded interaction of an illuminated particle with its own reflection.

Mirror-mediated cooling [1,2] is in essence a prototype of both the cavity-mediated cooling of atoms [3] and the cavity-cooling of interferometers [4]. It offers a new paradigm, by reducing the cavity to a single round-trip that can no longer be regarded as nearly closed or quasi-Markovian. A classical analysis is easily cast in three dimensions as an extension of optical binding [5,6,7], revealing new transverse cooling mechanisms and allowing the plain plane prototype to be extended to complex shapes and geometries including fibres, external resonators and amplifiers. Simple geometrical optics analysis gives a powerful insight, while a transfer matrix method allows a smooth progression from mirror-mediated to cavity-mediated mechanisms and Doppler cooling.

The weak basic phenomenon of mirror-mediated cooling may be enhanced by including geometric or material resonances, such as etalons, plasmon resonances, waveguides, narrowband filters, photonic crystals and whispering-gallery resonators, within the feedback path [8], to enhance the retardation upon which the effect depends. Separating the cooled particle from the resonator brings great experimental flexibility, including the ability to replicate the geometry in microfabricated arrays.

Similar resonances offer a means of enhancing dipole traps formed by the foci of steeply curved mirrors, while the complex ray paths and polarizing properties of such mirrors suggest their potential, together with planar permanent magnets, for tiny, replicable magneto-optical traps. We shall give a brief report of recent theoretical and experimental progress [9].

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Manipulation of small atom clouds in a microscopic dipole trap

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Recent years have seen a growing interest in the study of small, but dense cold atomic ensembles. Applications are ranging from the study of BECs outside the mean-field regime[1] to the storage of light in these dense samples. Here we present our work on the manipulation of cold atomic clouds in a regime where they contain only a few tens of atoms. In our case we use ^{87}Rb atoms, trapped in a microscopic optical dipole trap, to study this mesoscopic regime. We use a single atom to measure the resolution of our imaging system. This method provides a calibration of our detection scheme[2] which is useful to understand the regime where many atoms are trapped.

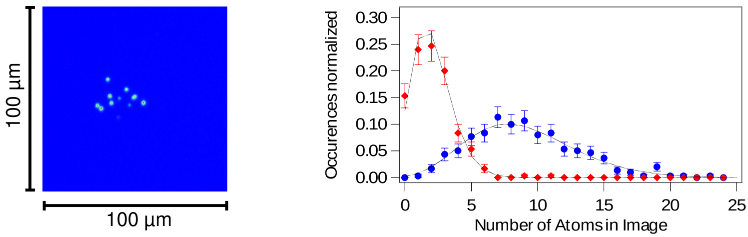

Figure 1: *(left) A typical image, that contains several photon events, taken by the CCD camera. (right) Histogram of the number of photon events counted on the CCD (diamonds: background, circles: atoms) for a trap with eight atoms on average.*

We implement an atom counting method that is capable of reconstructing the atom number distribution inside the dipole trap and allows to measure the average atom number precisely. This method relies on counting photon events on a CCD camera that are induced by a resonant probe sent on the atom and analyzing the photon number distribution obtained over a series of images (see Fig. 1). With these techniques in hand we perform measurements on the dipole trap losses in the presence of near resonant light. The results help to optimize the number of atoms loaded into the dipole trap and to understand the mechanism of subpoissonian dipole trap loading. Furthermore it may be useful for the realisation of a BEC with a few atoms only.

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Photoionization Cross-Section Measurements in a Rubidium Magneto-Optical Trap

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Photoionization cross-section measurements are relevant for fundamental tests of the atomic theory, as well as for state-selective detection of trapped atomic and molecular species and plasma research, including ultracold plasma formation. We have extended the current photoionization cross-section measurements of the $5P_{3/2}$ exited state of rubidium by including three additional wavelengths close to the ionization threshold of 479.1 nm. The measurements were performed in a rubidium magneto-optical trap using several lines from a mixed argon-krypton ion laser ranging from 457.9 nm to 476.5 nm. The photoionization rate at each wavelength was determined from the loss rate of atoms in the trap during exposure to the ionizing laser radiation. Our results are in good agreement with other experimental results and allow for comparison with theoretical predictions of the photoionization cross section versus the ionizing photon energy.

Single Permanent Magnetic Microtraps for Direct Forced Evaporative Cooling

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A simple three-wire-based magnetic microtrap for direct forced evaporative cooling of neutral atoms without using induced spin-flip has been proposed[1]. We introduce two simple permanent magnetic microstructures, for creating single 3D magnetic microtrap and direct forced evaporative cooling of neutral atoms without using spin-flip technologies to attain Bose-Einstein condensation. In each configuration, a bias magnetic field, $\mathbf{B}_1$, is applied to vary the trap depth, frequencies and minimum of absolute value of the magnetic field, B. According to the Figure 1, for an L-shaped configuration of permanent magnets, when B_{1z} changes from $-10G$ to $-7G$ the trap depth is reduced. As diagrams show, $x_{min} = 0$ but y_{min} and z_{min} change with the bias field. Figure 2 shows a U-shaped configuration of permanent magnets. When B_{1z} changes from zero to $5G$ the depth of the trap is decreased. The center of the microtrap remains at $x_{min} = y_{min} = 0$ and $z_{min} = 5.28\mu m$ while B_{1z} varies.

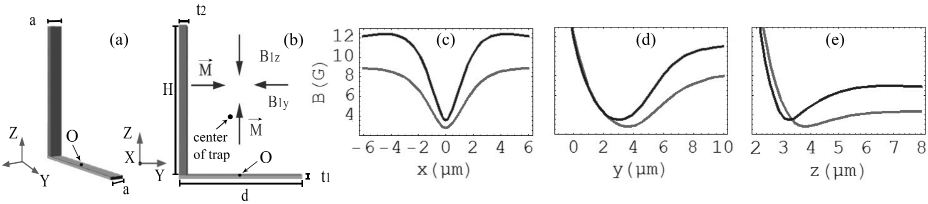

Figure 1: *(a and b): L-shaped configuration, where $a = 1\mu m$, $d = 10\mu m$, $H = 10\mu m$, $t_1 = 200nm$, $t_2 = 600nm$ and $4\pi M = 3800G$. (c-e): Plots of B along x, y and z directions, respectively. Here, $B_{1x} = 0$, $B_{1y} = -5G$ and the black and the grey lines are corresponding to $B_{1z} = -10G$ and $B_{1z} = -7G$, respectively.*

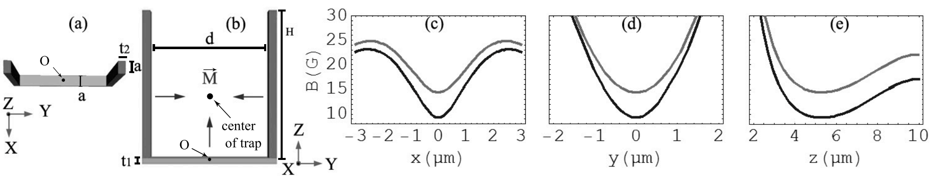

Figure 2: *(a and b): U-shaped configuration, where $a = 1\mu m$, $d = 8.8\mu m$, $H = 10\mu m$, $t_1 = 400nm$, $t_2 = 600nm$ and $4\pi M = 3800G$. (c-e): Plots of B along x, y and z directions, respectively. The black and the grey lines are corresponding to $B_{1z} = 0$ and $B_{1z} = 5G$, respectively. Here, we have $B_{1x} = B_{1y} = 0$.*

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Quantum dynamics of the dissociation of a condensate of dimers into fermionic atoms

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We numerically simulate the exact quantum many-body dynamics of bosonic dimers dissociating into fermionic atoms by applying a Gaussian phase-space representation[1].We quantify deviations of atom-atom pair correlations from Wick's factorization scheme, and show that atom-molecule and molecule-molecule correlations grow with time, in clear departures from pairing mean-field theories.

The accuracy for higher-order correlations is demonstrated by comparison with a standard matrix representation for small systems of 10 molecules and 10 atomic modes. We then give results for systems of $10^2 - 10^4$ molecules and 10^3 atomic modes, illustrating the potential capability of the phase-space representation for first-principles quantum dynamical simulations for fermionic systems of realistic sizes in current experiments.

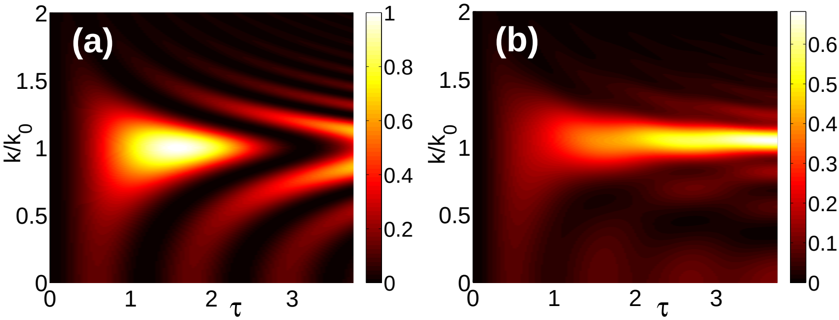

Figure 1: *The* exact *fourier-mode populations of the dissociated atom field. (a) Pauli-blocked regime with $N_0 = 10^4$ atoms; (b) Depleted pump regime with $N_0 = 100$ atoms.*

The Gaussian phase-space method provides an exact solution to quantum dynamics, as long as sampling error can be controlled. It can be viewed as providing the quantum corrections, through additional stochastic terms, to different mean-field approaches.

Extensions of this method to implement s-wave scattering interactions will allow us to study non-equilibrium dynamics in a broader class of fermionic model systems of current experimental interest, such as the Fermi Hubbard model and the BEC-BCS crossover problem.

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S-wave interactions in a quantum-degenerate two-species Fermi-Fermi mixture

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We investigate interactions in a quantum-degenerate Fermi-Fermi mixture of ^{6}Li and ^{40}K atoms with a large mass ratio[1]. We employ the method of cross-dimensional relaxation[2] [3] where a classical non-equilibrium cloud with different one-dimensional internal energy distributions relaxes through elastic collisions to thermal equilibrium. In our case of a non-equilibrated spin-polarized ^{6}Li-^{40}K mixture, the rethermalization is driven by pure s-wave interactions between the species. This system is ideal to study elastic collisions with different masses since intraspecies collisions are suppressed due to Pauli principle. For same initial conditions, i.e. same induced energy anisotropy and particle number for ^{6}Li and ^{40}K, the relaxation rate of the energy anisotropy is mass-dependent and ^{6}Li equilibrates faster in the mixture with ^{40}K as compared to the simultaneously proceeding relaxation of ^{40}K with ^{6}Li. With this method we characterize an interspecies s-wave Feshbach resonance located at 155.1 G. Elastic scattering cross sections are measured over a broad range of magnetic field values and a Fano-shaped profile is obtained. We locate highest scattering cross sections and a value for the width of the Feshbach resonance is experimentally determined. As reported recently, we successfully produced ultracold bosonic heteronuclear ^{6}Li-^{40}K molecules with long lifetimes at this specific resonance[4]. We relate already presented molecular lifetimes to scattering cross sections in the vicinity of the resonance.

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Description of collective modes in ultracold Fermi systems : dynamical approach and higher order in moment method.

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In a recent past, many experiments on ultracold trapped Fermi gases have studied collective oscillations in the normal-fluid phase. In order to explain the corresponding data, we have developed a theoretical approach that incorporates the in-medium effects[1] : Since Pauli blocking is crucial for intermediate states, the scattering matrix (or T matrix) of two fermionic atoms in a Fermi gas becomes different from that of two atoms in free space; this effect becomes particularly important near a Feshbach resonance, where the interaction in free space is very strong but becomes effectively suppressed in the medium. Thus we have calculated the in-medium T matrix in ladder approximation and studied its effects on the properties of collective modes of a trapped gas.

The in-medium interaction has been actually introduced on both sides of the Boltzmann equation, namely in the calculation of the mean field and in the calculation of the collision rate. By instance, this allowed us to explain the observed striking upward shift of the frequency of the quadrupole mode in the collisionless regime.

By including the mean field, we also improved considerably the agreement with the measured temperature dependence of frequency and damping rate of the scissors mode, whereas the use of the in-medium cross section deteriorates the description, in agreement with previous works.

To go further in the description, we numerically solved the Boltzmann equation using the test-particle method. The numerical results have been compared with those obtained previously by taking moments of the Boltzmann equation (method used by the experimentalists to determine the frequency and the damping of a mode). We have found that the general shape of the response function is very similar in both methods, but the relaxation time obtained from the simulation is significantly longer than that predicted by the method of moments. We have shown that the result of the method of moments can be corrected by including fourth-order moments in addition to the usual second-order ones and that this method agreed very well with our numerical simulations[2].

Furthermore the trap anharmonicity effects are shown to be small compared to the fourth-order correction.

[1]. [2].

[1] S. Chiacchiera, T. Lepers, D. Davesne and M. Urban, "Collective modes of trapped Fermi gases with in-medium interaction", Phys. Rev. A 79, 033613 (2009)

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The Pseudogap and Universal Relations in the BCS-BEC Crossover

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We present our recent experiments probing the pseudogap phase and verifying universal relations in the BCS-BEC crossover. To observe the pseudogap phase we make two independent measurements, namely the temperature of the superfluid phase transition and the single-particle spectral function. In our measurements, we observe no qualitative change in the spectral function even as the temperature of the Fermi gas is increased from below to above the superfluid transition temperature. This is strong evidence for a pseudogap in an atomic Fermi gas. Secondly, a recent theoretical advance in the study of strongly interacting fermions is the derivation of a number of exact universal relations that are predicted to be valid for all interaction strengths, temperatures, and spin compositions. These equations, referred to as the Tan relations, relate a microscopic quantity, the amplitude of the high-momentum tail of the fermion momentum distribution, to the macroscopic thermodynamics of the many-body system. We compare measurements of the potential and release energies of our gas to photoemission spectroscopy data and momentum distributions in order to test the predicted relations.

Confinement induced resonance in a quasi-2D Fermi gas.

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Quasi-2D Fermi gases provide a rich environment to explore many effects not present in 3D systems. To form a 2D Fermi gas the criterion $k_B T, E_f < \hbar\omega_z$ must be met. In our experiments an anisotropic 2D optical potential is formed by an elliptical Gaussian beam produced by tightly focusing a circular Gaussian beam in one direction with a cylindrical lens[1,2]. The trapping frequencies are $\omega_z/2\pi \approx 4$ kHz in the tightly confined direction and $\omega_r/2\pi \approx 70$ Hz in the weakly confined direction giving a trap aspect ratio of ∼60. Recently E. Haller *et al.*[3] reported the observation of a confinement induced resonance (CIR) in a 1D Bose gas of ^{133}Cs atoms close to a Feshbach resonance. A CIR arises when the transverse harmonic oscillator length $a_z = \sqrt{\hbar/m\omega_z}$ approaches the 3D s-wave scattering length a_{3D}. A pole in the scattering length emerges which dramatically changes the dynamical properties of the gas.

In this paper we report the observation of a confinement induced resonance for an ultracold quasi-2D Fermi gas of ^{6}Li atoms in the vicinity of the Feshbach resonance at 834 G. The ability to precisely tune the interactions between fermions of different spin states using a magnetic Feshbach resonance allows an investigation of this property in a quasi-2D Fermi gas across the BEC-BCS crossover.

The CIR is observed by measuring the transverse width of the atom cloud containing ∼4000 atoms after a short time of flight. Figure 1 shows a peak at 816 G corresponding to transversely excited molecules. This is a confinement induced resonance in which the threshold energy of two colliding ground state atoms becomes resonant with molecules in the first excited state at a particular value of the scattering length. The inset shows the usual monotonic increase in the cloud width (release energy) from the 3D trap across the BEC-BCS crossover.

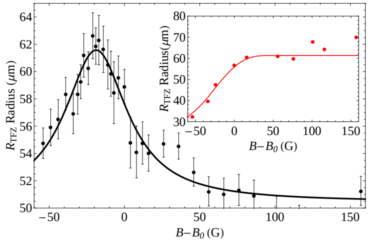

Figure 1: *Observed width of a ^{6}Li quasi-2D Fermi gas for a fixed expansion time of 1.5 ms with a trap frequency of $\omega_z/2\pi = 4160$ Hz. Inset: Width from a 3D optical trap.*

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First Principle Many-Body Theory for Strongly Interacting Ultracold Fermi Atoms

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Recent breakthroughs in the creation of ultra-cold atoms in the laboratory have ushered in major changes in physical science. These enormous changes in the coldest temperatures available in the laboratory mean that many novel experiments are possible. There is unprecedented control of interaction, geometry and purity in these novel systems, meaning that quantum many-body theory is now facing severe challenges in quantitatively understanding these new results. Here, we discuss some of the new experiments on strongly interacting fermions and recently developed theoretical techniques that are proving successful today in understanding the experimental results. These are: (a) Infinite order perturbation theory [1] [2]; (b) High temperature quantum cluster expansion [3] [4] [5]; (c) Exact solutions for few-particle systems; (d) Asymptotically exact relations for structure factor.

[1]Hui Hu, Xia-Ji Liu, and Peter D. Drummond, Europhys. Lett. 74, 574 (2006)
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[3]Xia-Ji Liu, Hui Hu, and Peter D. Drummond, Phys. Rev. Lett. 102, 160401 (2009)
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[5]Hui Hu, Xia-Ji Liu, Peter D. Drummond, and Hui Dong, arXiv:1003.1538v1 (2010).

Strong Coupling Effect on Normal State of Fermi gas with a p-wave interaction

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We investigate one-particle excitations in an ultracold one-component Fermi gas with a p-wave interaction at and above the superfluid transition temperature T_c. Extending the strong coupling theory, which is developed in the case with an s-wave interaction[1], to the case with a p-wave interaction, we calculate the one-particle density of state (DOS), as well as spectral weight (SW) and show the so-called pseudogap behavior in DOS. This phenomena is caused by a pairing fluctuation associated with the strong-pairing interaction and considered as a precursor of a p-wave superfluid phase. Experimentally, although the p-wave Feshbach resonance has been recently observed in ^{40}K [2] and ^{6}Li [3] Fermi gases, the p-wave superfluid phase in these systems has not been realized yet, due to some experimental difficulties. Thus the observation of the pseudogap as a precursor of a p-wave superfluid phase can be useful to know how the system is close to the phase transition. We will discuss how the pseudogap in DOS and SW varies as one approaches T_c from the normal state, over the entire region of interaction. This work was supported by Global COE Program "High-Level Global Cooperation for Leading-Edge Platform on Access Spaces (C12)".

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Ultracold Bose-Fermi mixture in a triple-well ring.

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We analyse the ground state properties of an ultracold Bose-Fermi mixture in a small size system. Namely, we consider a triple-well ring potential in the limit of small particle numbers. By means of the direct diagonalisation of the three-site Bose-Fermi-Hubbard ring model [1], we show that the ground state symmetries play a fundamental role in the formation of phases with superfluid and insulating properties. Both repulsive and attractive inter-species (U_{bf}) and boson-boson interaction (U_{bb}) are considered.

The system is characterised by means of spatial (tunneling) correlations for each of the atom species $\eta = |\langle \hat{a}_i^\dagger \hat{a}_{i+1} \rangle|/n$, where $\hat{a}^\dagger$ and $\hat{a}$ are creation and annihilation operators and n is the filling factor. The boson tunnelling correlation, η_f, for the fermion filling $n_f = 1/3$ is plotted in Fig. 1. The system is particle-hole symmetric with respect to the change of the interspecies interaction sign, i.e. repulsion at 1/3 filling of fermions is equivalent to attraction at 2/3 filling. As one increases interaction strengths the system moves to an insulating phase characterised by suppressed spatial correlations. In contrast to the pure Bose system [2], new insulating phases appear in the mixture that are due to inter-species interactions (see Fig. 1). These phases are characterised by large particle number fluctuations in the system.

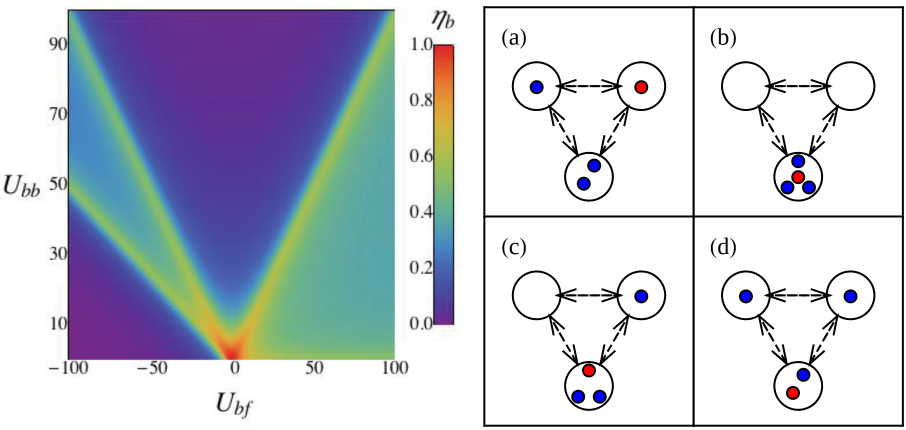

Figure 1: *Density plot of the boson tunnelling correlation, $\eta_b(U_{bf}, U_{bb})$ (left) and the ground state configurations of the insulating states (right). Where (a) and (c) correspond to the regions for $U_{bb} > 0$ and $U_{bb} < 0$ in between the maxima in η_b, (b) corresponds to the insulating state for strong attraction ($U_{bf} \ll 0$), and (d) is the "standard" bosonic insulating state ($U_{bb} > |U_{bf}| \gg 0$).*

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Quantization function for attractive potential tails

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Potential wells with tails falling off faster than $1/r^2$ support at most a finite number of bound states; their energies $E_n = -\hbar^2\kappa_n^2/(2M)$ are related to their quantum numbers

$$n = 0,\, 1,\, 2, \ldots \quad \text{via a quantization rule} \qquad n_{\rm th} - n = F(E_n)\ , \tag{1}$$

where $n_{\rm th}$ is the not necessarily integer threshold quantum number. For deep potentials with attractive tails, the *quantization function* $F(E)$ is largely determined, at near-threshold energies, by a contribution $F_{\rm tail}$ due to the potential tail, while short-range properties of the potential enter via a weakly energy dependent contribution $F_{\rm sr}$:

$$F(E) = F_{\rm tail}(E) + F_{\rm sr}(E)\ , \quad F_{\rm sr}(E) \overset{E\to 0}{\sim} \gamma_{\rm sr}E + O\left(E^2\right)\ . \tag{2}$$

For a homogeneous tail, $V_{\rm tail}(r) = -\dfrac{C_\alpha}{r^\alpha} = -\dfrac{\hbar^2(\beta_\alpha)^{\alpha-2}}{2M\,r^\alpha}$, $F_{\rm tail}$ is a universal function depending only on the product $\kappa\beta_\alpha$. For $\kappa\beta_\alpha \gg 1$, the energy dependence of $F_{\rm tail}$ is accurately given by WKB quantization [1] and is proportional to $(\kappa\beta_\alpha)^{1-2/\alpha}$. Closer to threshold, quantum effects lead to a universal behaviour similar to the effective-range expansion of scattering theory,

$$F_{\rm tail}(E) \overset{\kappa\to 0}{\sim} b\kappa/\pi + (d\kappa)^2/2\pi\ , \tag{3}$$

with analytically known α-dependent length parameters b and d. The quantization function can be expressed in terms of exact solutions of the Schrödinger equation [2] or, more conveniently, by appropriate interpolation [3] between the low-κ limit (3) and the semiclassical high-κ limit.[1] Fig. 1 shows, in a range accommodating the highest three bound states, the quantization function for potential tails proportional to $-1/r^4$ and to $-1/r^6$.

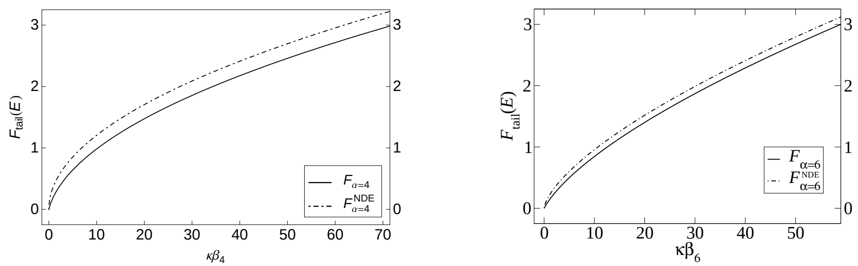

Figure 1: *Quantization function* $F_{\rm tail}$ *as function of* $\kappa\beta_\alpha$ *for* $\alpha = 4$ *(left) and* $\alpha = 6$ *(right). The dot-dashed lines show the WKB results* [1] *proportional to* $(\kappa\beta_\alpha)^{1-2/\alpha}$.

Explicit analytical expressions for $F_{\rm tail}$, which reproduce the exact functions with an error near 10^{-4} or less all the way from threshold to the high-κ limit, are given in Refs.[3], and their usefulness is demonstrated in several concrete applications to vibrational states of diatomic molecules ($\alpha = 6$) and of the H_2^+ molecular ion ($\alpha = 4$).

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[3] P. Raab, H. Friedrich, Phys. Rev. A **78** (2008) 022702; **80** (2009) 052705

Study of Efimov physics in two different spin states of the same atomic system

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We experimentally investigate three-body recombination loss in a gas of ultracold ^{7}Li atoms prepared in two different spin states in the vicinity of two different Feshbach resonances. We report that in the regime of universality the positions and widths of recombination minima for positive scattering lengths and Efimov resonances for negative scattering lengths are identical for both states within the experimental errors (see Fig. 1). The absolute locations and lifetimes of Efimov features are defined by the short-range part of the three-body potential which is usually treated in terms of a three-body parameter[1]. Therefore our measurements indicate that the three body parameter at high magnetic fields is spin independent[2].

Moreover, we found that the relation between locations of the observed features are in an excellent agreement with the universal theory and in that sense we support the famous universal scaling factor, $\exp(\pi/s_0) \approx 22.7$ where $s_0 = 1.00624$.

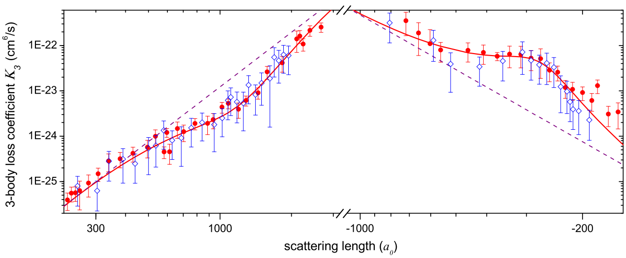

Figure 1: *Experimentally measured three-body loss coefficient K_3 as a function of scattering length (in units of Bohr radius a_0) across a Feshbach resonance at $\sim$ 740 G on the $|F = 1, m_F = 1\rangle$ absolute ground state (red solid circles). The solid lines represent fits to the analytical expressions of universal theory. The dashed lines represent the a^4 upper (lower) limit of K_3 for $a > 0$ ($a < 0$). K_3 values across a Feshbach resonance at $\sim$ 895 G of the one but lowest Zeeman state ($|F = 1, m_F = 0\rangle$) are represented by blue open diamonds*[3].

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RF-Spectroscopy of Efimov Trimers

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Since the first signatures of Efimov states were found in the rate of inelastic collisions of an ultracold atomic gas, Efimov physics has rapidly developed into a new field of study which has gained widespread recognition. However, until now experiments have been limited to observations of the crossings of Efimov states with the continuum. With this poster we report on the first direct observation of an Efimov state with radio-frequency (RF) spectroscopy. We have measured the binding energy of this Efimov state as a function of interaction strength and found good agreement with theoretical predictions. This work opens the door for both precision studies and coherent manipulation of Efimov trimers.

Backaction of ultracold atoms on a mechanical oscillator

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We report the observation of a mechanical backaction of ultracold atoms onto the vibrations of a single mode of a mechanical oscillator. The atoms are trapped in a red detuned 1D optical lattice provided by a laserbeam, which is retroreflected at the mechanical oscillators' surface. Motion of the mechanical oscillator shakes the lattice and couples the oscillators' to the atoms' motion. On the other hand, the motion of the atoms leads to a redistribution of photons between the two running wave components forming the lattice and is thus imprinted on the power of the laser beam that is retroreflected at the oscillator. The resulting modulation of the radiation pressure constitutes the backaction of the atoms onto the mechanical oscillator, which we observe in oscillator ringdown measurements.

In collaboration with the group of P. Zoller, a fully quantized description of this system was formulated[1].

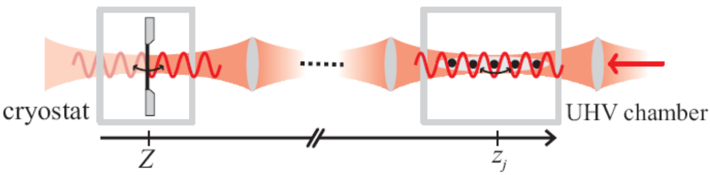

Figure :: *A laser field impinging from the right is partially reflected off a dielectric membrane and forms a standing wave optical potential for an atomic ensemble. Vibrations of the membranes fundamental mode will shift the standing wave field, shaking atoms in the optical lattice. Conversely, oscillations of the atomic cloud (center of mass motion) will change the intensity of left/right propagating field components, thus shaking the membrane via changing the radiation pressure on it. In the experiments presented, the mechanical oscillator is in a room temperature environment, however, due to the long distance coupling, it could be also mounted inside a cryostat.*

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Slowing and stopping light using an optomechanical crystal array

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One of the major advances needed to realize all-optical information processing of light is the ability to delay or coherently store and retrieve optical information in a rapidly tunable manner. In the classical domain, this optical buffering is expected to be a key ingredient to managing the flow of information over complex optical networks. Such a system also has profound implications for quantum information processing, serving as a long-term memory that can store the full quantum information contained in an optical pulse. Here we suggest a novel approach to light storage involving an optical waveguide coupled to an optomechanical crystal array, where light in the waveguide can be dynamically and coherently transferred into long-lived mechanical vibrations of the array all-optically. Our scheme combines many of the best attributes of previously proposed approaches[1,2], in that it simultaneously allows for large bandwidths of operation, on-chip integration, relatively long delay/storage times, and ease of external control. Beyond light storage, this work opens up the intriguing possibility of a platform for quantum or classical all-optical information processing using mechanical systems.

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Entangling bright polaritons in a nano-mechanical cavity

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There have recently been a great interest in creation of quantum entanglement in optomechanical systems.[1] This interest stems from the possibility of the development of new practical techniques for engineering of entangled states of macroscopic systems through interactions with mechanical oscillators. With the recent progress in laser cooling techniques, fabrication of low-loss optical elements and high-Q mechanical resonators, it is now possible to prepare nanomechanical oscillators that can be controlled to a very hight precision and can even reach the quantum level of the oscillations.

In this presentation, we consider a finite size one-dimensional optical lattice located inside a single-mode cavity with one fixed partially transmitting mirror and one movable perfectly reflecting mirror. The optical lattice is composed of N regularly spaced and non-overlapping sites.[2] Each site contains a single atom modeled as two-level systems with ground state $|g_n\rangle$ and excited state $|e_n\rangle$, separated by the transition frequency ω_a and connected by a transition dipole moment $\vec{\mu} = \langle e_n|\vec{\mu}_n|g_n\rangle$. The motion of the movable mirror is modeled as a quantum mechanical harmonic oscillator of mass m and resonant frequency ω_m. The cavity mode is driven by an external laser field which is treated classically and considered as a source of the radiation pressure force on the movable mirror.

We work in terms of the collective excitation modes (excitons) that combined with the cavity mode form along with it a single "polariton" quantum system. We show several interesting features of the system. In the first place, we find that in the absence of the mechanical oscillator the system consists of two completely decoupled bright polaritons, both damped with the same rate γ. The effect of the mechanical oscillator is to introduce both shifts of the frequencies and coupling between the polaritons. If the harmonic oscillations are treated classically, the effect of the mechanical oscillator is to destroy the polaritons. On the other hand, if initially the exciton and the cavity fields were disentangled, the effect of the mechanical mode is to entangle them. However, the resulting polariton modes are found be maximally entangled only in the limit of infinitely large coupling constant of the oscillator to the cavity mode. We also consider an initial non-maximally entangled state between the exciton and the cavity modes and find that the state can be transferred to the maximally entangled state by the mechanical effect only for positive detunings of the exciton and the cavity mode frequencies. Otherwise, for negative detunings, the polaritons cannot be transferred by the mechanical effect into the maximally entangled state.

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Cold atoms near superconductors

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Hybrid quantum systems, which combine ultra-cold atoms with solid state devices, have attracted considerable attention in the last few years. Promising applications have been proposed in the areas of precision sensing and quantum information processing. We report on our experimental efforts towards the realization of such systems based on ultracold atoms and superconductors.

We describe the experimental system, that consists of a rubidium BEC apparatus and a thermally shielded helium flow cryostat at 4.2 K, both in the same ultrahigh vacuum chamber. Atom clouds are transported from the BEC setup to the cryogenic region by means of optical tweezers.

We report on the measurement of atomic spin coherence near the surface of a superconducting niobium wire. As compared to normal conducting metal surfaces, the atomic spin coherence is maintained for time periods beyond the Johnson noise limit[1]. The result provides experimental evidence that magnetic near field noise is strongly suppressed close to the superconductor. For very small distances to the wire surface, we observe the impact of the Meissner effect on the trap parameters[2,3] and we measure the temperature dependence of magnetic flux penetration into the type-II superconductor.

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Ultracold Quantum Gases near Carbon Nanotubes

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In an experimental approach based on magnetic microchips, we investigate the interaction between ultracold atoms and carbon nanotubes (CNTs). The tubes with widths of 50 nm and heights up to 20 μm are vertically aligned on top of a silicon chip surface and arranged in different patterns ranging from nano-carpets up to individual free standing CNTs. In combination with a conventional atom chip, we are able to prepare ultracold atoms and Bose-Einstein condensates close to these tubes (see Fig. 1).

In a first experiment, we use ultracold atoms to map the surface topography of nanotube patterns and individual free standing CNTs. Besides a precise nanotube height measurement, this gives access to the lateral calibration of the cloud position with respect to the tubes. Observing atomic loss rates for different cloud temperatures and tube distances, we measure the inelastic scattering rate at a single free standing CNT. In comparison with the rates measured above a plain surface, we deduce the scattering rate solely limited by the nanotube and calculate the corresponding inelastic scattering cross section in the low energy limit. The scattering cross section largely exceeds the geometrical cross section and allows for a first approximation of the corresponding Casimir-Polder potential.

In a second experiment we apply high voltage to a nanotube arrangement which is illuminated by a bright atomic rubidium source. Due to the small radius and the high aspect ratio of the nanotubes the electric field is largely increased at the CNT tip and allows for field ionization of nearby atoms. In combination with a sensitive ion detector we demonstrate a detector for ground state atoms with single atom sensitivity and high spatial and temporal resolution [1].

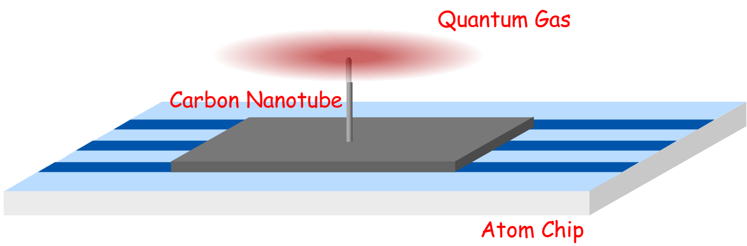

Figure 1: *Using magnetic microchips, ultracold quantum gases are brought in close proximity to a single carbon nanotube. This allows for measuring interactions between ultracold atoms and CNTs.*

[1] B. Grüner, M. Jag, A. Stibor, G. Visanescu, M. Häffner, D. Kern, A. Günther & J. Fortágh "Integrated atom detector based on field ionization near carbon nanotubes", Phys. Rev. A **80**, 063422 (2009)

Extreme Ultraviolet Frequency Comb via Intracavity High Harmonic Generation

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Precision spectroscopy in the vacuum and the extreme ultraviolet (EUV) spectral regions is interesting for a variety of scientific applications, ranging from the development of the next generation "nuclear" clocks to tests of QED in atomic systems. Progress in this region, however, is hampered by the lack of narrow linewidth cw lasers. A very promising method for overcoming this limitation is high harmonic generation (HHG) at high repetition frequencies by coupling a frequency comb to a high finesse optical enhancement cavity, which is necessary to reach the required peak intensities. A first-generation fiber-based system was able to achieve $\sim$ 100 nW of average power up the 21st harmonic at 51 nm [1]. Here we present, power scaling of this technique using a new 80-W average power Yb fiber laser with 120 fs pulse duration at repetition rate of 154 MHz [2]. Using 15 W of average power from this laser, we have achieved intracavity average power of 5 kW, corresponding to 6×10^{13} W/cm^2 intensity at the focus. The harmonic yield outcoupled via an intracavity diffraction grating[1] is shown in Fig 1. The measured harmonic powers range from 1 to 4 μW for 17th through 9th harmonics.

In addition to power scaling, the phase coherence of the harmonics is important for the generation of an EUV frequency comb. Interferometric measurements of pulse to pulse coherence for the 7th harmonic at 156 nm have put an upper limit of 20 MHz on the comb teeth linewidth[3]. We are currently working on extending the test of phase coherence to the 13th harmonic by performing direct frequency comb spectroscopy of a supersonic argon beam at 82 nm. Preliminary results from this effort will be discussed.

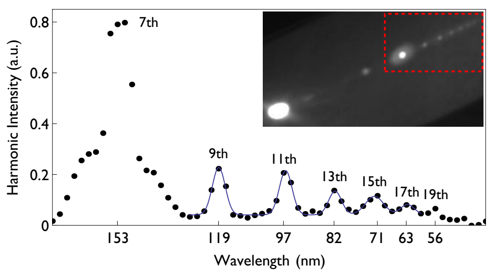

Figure 1: *The high harmonic spectrum. Inset shows the CCD image of a sodium salicylate plate with the relevant harmonics in dashed box.*

[1]I. Hartl et al., Opt. Lett. 32, 2870-2872 (2007); D. C. Yost et al., Opt. Lett. 33, 1099 (2008).
[2]A. Ruehl et al., in Conference on Lasers and Electro-Optics/International Quantum Electronics Conference, OSA Technical Digest (CD) (Optical Society of America, 2010), paper CMN1.
[3]D. C. Yost et al., Nature Physics 5, 815 - 820 (2009).

Phase-Matched High Harmonic Generation for Study of Rotational Coherent Molecular Dynamics

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Coherent extreme ultraviolet (XUV) radiation and soft X-ray radiation are currently finding wide application in physics, chemistry, and biology [1]. Coherent XUV radiation can now be produced by high-order harmonic generation (HHG) of highly energetic femtosecond laser pulses in atomic [2] or molecular gases [3]. The phase-matched propagation of the fundamental and HHG radiation is reflected in the harmonic intensity. The degree of phase-matching depends on the harmonic order and experimental parameters including the atomic and molecular electronic and geometric dispersion, the absorption coefficient of the target gas at the harmonic frequencies and the ionization fraction of the gas and the gradient of the atomic and molecular dipole phase. Many of these parameters depend on the molecular alignment, the static molecular structure, and the dynamics. When the interaction length of the generation process is long not only single-molecule effects but also macroscopic phase-matching play an important role in determining the alignment dependence of the harmonic signal from a molecule [4]. In this paper, we show that by using an off-axis femtosecond beam for field free aligned molecules, the phase-matched HHG process in diatomic molecular gases reflects Raman coherence clearly . The modulation of the HHG intensity due to changes in the nonlinear refractive index is used to study rotational coherence in the ground state of molecules.

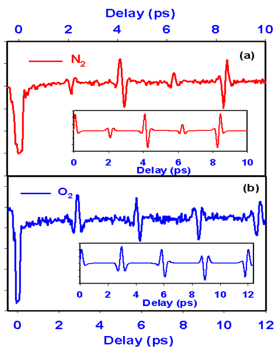

Figure 1: *Intensity of the H27 of aligned N_2 (a) and H21 of aligned O_2 (b) versus delay between the two beams. Insets: change of nonlinear refractive index due to Raman rotational motion as a function of delay between the probe and the pump beams.*

[1] A. Rundquist, C. G. Durfee III, Z. Chang, C. Herne, S. Backus, M. Murnane, and H. C. Kapteyn, Science 280, 1412-1415, 1998

[2] L. V. Dao, S. Teichmann, J. Davis and P. Hannaford, J. Appl. Phys. 104, 023105, 2008

[3] N. Hay, R. Velotta,M. Lein, R. de Nalda, E. Heesel, M. Castillejo, and J. P. Marangos, Phys. Rev. A, 65, 053805, 2002

[4] B. A. Sickmiller and R. R. Jones, Phys. Rev. A 80, 031802, 2009

Amplification of XUV radiation in a dual-gas high-harmonic generation system

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Recent developments in few-cycle, mode-locked lasers and carrier-envelope phase stabilisation are allowing for electron-atom dynamics to be studied on attosecond timescales through the generation of XUV high-harmonics[1]. The intense electric field that is present in ultrashort laser pulses is sufficient to suppress the Coulomb barrier of an electron orbiting a nucleus such that the electron will undergo either tunnel or above-barrier ionisation[2]. After three or four quarters of an optical period, the electron re-collides with the parent ion resulting in the emission of a high energy photon. The periodicity of these ionisation and re-collision events is determined by the carrier laser oscillation which results in photons being generated at odd harmonics of the carrier frequency. This process is known as high-harmonic generation (HHG) and a typical spectrum will extend into the XUV and soft x-ray region[3].

We plan to investigate parametric amplification of high-harmonic radiation with the aim of increasing the yield of the harmonics that can be used to form isolated attosecond pulses. The experiment involves producing high-harmonic radiation in a neon gas jet and then using this to seed a second gas jet that acts as an amplifier whose gain is dependent on the pressure of this secondary species. Seres *et al*[4] have demonstrated a small signal gain of up to 8×10^3 in argon and helium using a single generation and amplification medium. This experiment will utilise the laser system of the Australian Attosecond Science Facility which consists of an amplified Ti:Sapphire mode-locked laser that produces 5.3 fs pulses with 0.4 mJ energy and a spectral FWHM of 180 nm at a central wavelength of 800 nm. The *f-2f* interferometer technique that was devised by Udem *et al*[5] is used to control the carrier-envelope phase of the few-cycle laser pulses.

[1]S. Kazamias, D. Douillet, et al., Physical Review Letters **90(19)** (2003).
[2]T. Brabec and F. Krausz, Rev. Mod. Phys. **72**, 545-591 (2000).
[3]A. Baltuska, T. Udem, et al., Nature **421**, 611-615 (2003)
[4]J. Seres, E. Seres, et al., Nature Physics (published online 18/04/2010).
[5]T. Udem, R. Holzwarth and T.W. Hansch, Nature **416**, 233-237 (2002).

Feshbach Resonance in Optical Lattices and the Quantum Ising Model

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Motivated by experiments on heteronuclear Feshbach resonances in Bose mixtures, we investigate s-wave pairing of two species of bosons in an optical lattice. The zero temperature phase diagram supports a rich array of superfluid and Mott phases and a network of quantum critical points. This topology reveals an underlying structure that is succinctly captured by a two-component Landau theory. Within the second Mott lobe we establish a quantum phase transition described by the paradigmatic longitudinal and transverse field Ising model. This is confirmed by exact diagonalization of the 1D bosonic Hamiltonian. We also find this transition in the homonuclear case.[1,2]

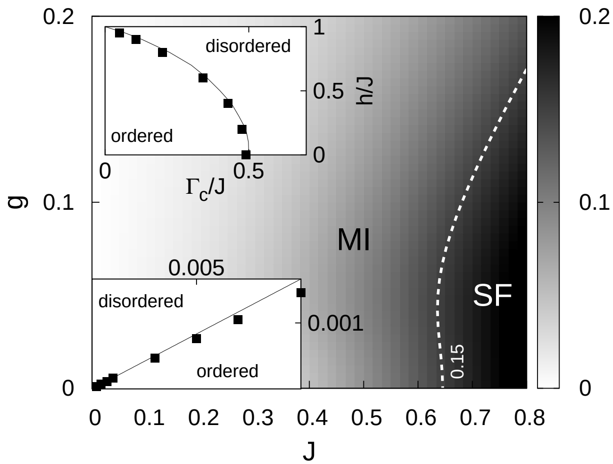

Figure 1: *Ising quantum phase transition occurring within the second Mott lobe as a function of the Feshbach coupling, g, hopping J, and longitudinal magnetic field, h.*[1,2]

[1]M. J. Bhaseen, A. O. Silver, M. Hohenadler, B. D. Simons, *Feshbach Resonance in Optical Lattices and the Quantum Ising Model*, Phys. Rev. Lett. **103**, 265302 (2009).
[2]M. Hohenadler, A. O. Silver, M. J. Bhaseen, B. D. Simons, *Quantum Phase Transitions in Bosonic Heteronuclear Pairing Hamiltonians*, `arXiv:1004.4497`.

Investigating dressed matter waves in periodic potentials

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Ultra-cold atoms and Bose-Einstein condensates (BECs) in optical lattices are a valuable tool for investigating quantum phenomena and simulating solid-state systems. Single ultra-cold neutral atoms can act as qubits for quantum information storage and processing. By exploiting the peculiar characteristics of periodically forced systems of ultra-cold gases in optical lattices, it was demonstrated how driving an optical lattice with a time-periodic force can change the tunneling rate between two lattice sites independently of the atom-atom interaction [1]. By adiabatically transferring a BEC from the ground state of a static lattice to the lowest quasienergy state of a driven lattice, we observed the quantum phase transition to a dressed Mott insulator regime, thus realizing an example of coherent control exerted by means of time-periodic forcing on a quantum phase transition. Using this technique, a many-body ground state with modified fundamental properties - a dressed matter wave - has been adiabatically created [2].

Our methods can be applied, for example, to time-periodic polychromatic driving, which shows a rich transport and localization behaviour. Furthermore, we have recently verified that strong driving can lead to a negative value of the tunnelling parameter (impossible to create with static potentials), with the system then occupying a single Floquet state, just as it occupies a single energy eigenstate when there is no forcing. Such systems with a negative value and/or anisotropy of the tunneling energy may produce new quantum phases. In a triangular lattice, such a negative tunneling energy can, for instance, mimic frustrated spin systems and also simulate other complicated Hamiltonians that are difficult to study in solid state materials [3].

Financial support by EU Network ”EMALI, by EU-STREP ”NAMEQUAM” and by CNISM ”Progetto Innesco 2007” is gratefully acknowledged.

[1] H. Lignier, C. Sias, D. Ciampini, Y. Singh, A. Zenesini, O. Morsch, and E. Arimondo, Phys. Rev. Lett. **99**, 220403 (2007).

[2] A. Zenesini H. Lignier, D. Ciampini, O. Morsch, and E. Arimondo, Phys. Rev. Lett. **102**, 100403 (2009).

[3] A. Eckardt P. Hauke, P. Soltan-Panahi, C. Becker, K. Sengstock, and M. Lewenstein, Europhys. Lett. **89**, 10010 (2010).

Many-body state preparation and heating of cold atoms in optical lattices

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[2]*Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria*

Recent experimental advances with ultracold quantum gases in optical lattices have made possible the realisation and study of microscopic lattice models that are used to describe complex phenomena in solid state physics. This opens opportunities to probe quantum many-body phenomena that are difficult to observe in solid-state systems, and to explore new aspects of the system, including coherent and dissipative many-body dynamics. However, the production of strongly interacting many-body states at very low temperatures, as required for the investigation of many interesting phenomena, remains a key challenge in current experiments.

In this context, it is important (i) to investigate new possible means for preparation of low-temperature many-body states, and (ii) to characterise and control heating processes arising from various experimental sources.

In the first part of this work, we study the use of adiabatic state preparation methods to produce a excited many-body state in an optical lattice, the η-condensate[1], which is an exact eigenstate of the Fermi-Hubbard model. We have studied how such a condensate can be prepared with high fidelity using an optical superlattice ramp, beginning from a band insulator[2], which can be produced with low entropy. Here, the excited state is obtained by means of a fast switch in the interaction strength, followed by adiabatic removal of the superlattice. Studying production of a known state provides a clear test of the use of adiabatic state preparation, and the excited eigenstates produced could also offer a sensitive means to reveal and characterize errors in the implementation of Hamiltonians in experiments.

In the second part of this work, we investigate heating of many-body states in an optical lattice. This involves an interesting interplay between essentially single-particle heating processes and many-body physics, as some interacting many-body states can be more sensitive to heating from a given source than others. We focus in detail on the heating of bosons in an optical lattice due to incoherent scattering of light from the lasers forming the lattice. We characterise the effects on many-body states for various system parameters, where we observe important differences in the heating for strongly and weakly interacting regimes, as well as a strong dependence on the sign of the laser detuning. We compute heating rates and changes to characteristic correlation functions based both on perturbation theory calculations, and a time-dependent calculation of the dissipative many-body dynamics. The latter is made possible for 1D systems by combining t-DMRG methods with quantum trajectory techniques.

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[2]A. Kantian, A. J. Daley, and P. Zoller, Phys. Rev. Lett, in press (arXiv:0911.2005)

Extracting quantum critical properties of Superfluid-Mott insulator transition of bosonic atoms in a realistic (finite temperature and finite trapping potential) experiment

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We present the direct comparison between the in-situ experimental observation[1] and ab-initio numerical calculation for ultracold bosonic atoms inside two-dimensional optical lattice using exact quantum Monte Carlo simulation[2]. Detailed density profile in non-uniform system can be used to map out the finite temperature phase diagram which is consistent with the phase diagram of a uniform system. We suggest a scheme to extract energy gap from a non-uniform (within a harmonic trap) system by scaling the compressibility with temperature at commensurate filling. Further possibilities to access other physical quantities for uniform systems from non-uniform finite temperature systems are also discussed.

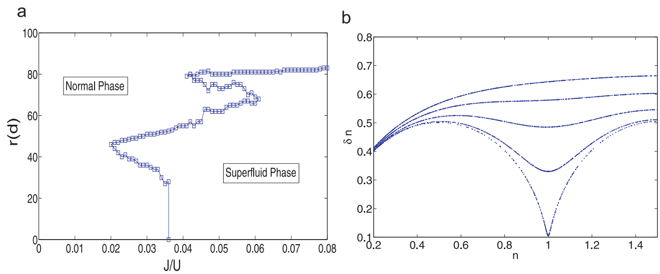

Figure 1: *(a)Finite temperature phase diagram for repulsive Bose-Hubbard model mapped from non-uniform system by compressibility. (b) The density fluctuation(related to compressibility) as function of density at different temperatures for non-uniform systems. We use real experimental parameters at optical lattice strength* $16E_R$ *with temperature from 2nK(bottom) to 10nK(top) for every 2nK.*

[1]Nathan Gemelke, Xibo Zhang, Chen-Lung Hung and Cheng Chin, Nature 460, 995 (2009)
[2]Lode Pollet, Kris Van Houcke and Stefan M.A. Rombouts, J. Comp. Phys. 225, 2249-2266 (2007)

Probing quantum gases in optical lattices by momentum-resolved Bragg spectroscopy

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Superfluid systems realized by ultracold quantum gases in optical lattices cover a wide range of tunable parameters, with a continuous connection to the regime of strong correlation. For full experimental access and a detailed comparison with condensed matter systems, there is a need for new detection techniques to probe their fundamental behaviour, characterized i.e. by the dynamic structure factor. We report on a comprehensive study of quantum gases in optical lattices by Bragg spectroscopy and present fully momentum resolved measurements of the band structure and associated interaction effects at several lattice depths. In addition, we directly study the momentum composition of excitations in this system and observe strong indications for Bogoliubov backscattering[1]. Furthermore we present measurements with Bragg spectroscopy in the intermediate and strongly correlated regime, in which we track the excitation gap of the Mott phase into the superfluid regime, revealing the transition to topically discussed excitations like the Amplitude mode [2]. We expand our analysis with the incorporation of lattice depth modulation spectroscopy and compare our results to recent numerical simulations. Our measurements are a promising basis for further detailed studies of strongly correlated phases, quantum gas mixtures and novel quantum phases.

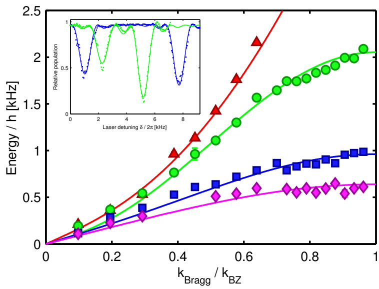

Figure 1: *Excitation energies with respect to momentum transfer k_{Bragg} for a harmonic confinement (triangles) and the nodal direction of a square lattice with depths or $V_0 = 3E_r$ (circles), $7E_r$ (squares) and $11E_r$ (diamonds). The inset depicts exemplary spectra for $V_0 = 3E_r$ and $7E_r$ showing the opening of the bandgap.*

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[2] S. D. Huber et al., "Dynamical properties of ultracold bosons in an optical lattice", Phys. Rev. B **75**, 085106 (2007)

Equilibration and Thermometry of Optical Lattice Antiferromagnets

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[2] *QUANTOP, The Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen , Denmark*

Antiferromagnetism occupies a central place in the study of strongly-correlated electron systems. Cold atoms in optical lattices offer a unique system to study antiferromagnets. However, it is unclear to what extent one can prepare and probe a stable antiferromagnet in such systems. To help address this question, we study the equilibration of optical lattice antiferromagnets following a generic preparation procedure in two or three dimensions. We find that equilibration of the spin degrees of freedom occurs at fixed energy and magnon number. We discuss the potential for spin thermometry in these systems and identify two experimentally accessible variables that allow one to extract the temperature and chemical potential.

A real-time controllable Brownian Motor realized with cold atoms in optical lattices

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Brownian motors are devices that can rectify noise into work or directed motion and are believed to be the driving mechanism of biological motors. The magnitude and direction of the motion is dependent on an asymmetry in the system, in accord with the Curie principle. To work, it also requires that the system is brought out of thermal equilibrium with the noise, in agreement with the second law of thermodynamics. We here demonstrate a Brownian motor, realized with cold atoms interacting with optical lattices, where the asymmetry, and hence also the induced drift, is controllable in real time in three dimensions. We show that the system has a close to instantaneous response to the changes in asymmetry, and we demonstrate an external real-time steering of the induced drift (Fig 1), as well as drifts along pre-designed paths (Fig 2). Our system also uses a method of detection that enables the implementation of real-time feedback. With this highly-controllable system, characteristic values such as rectification efficiency and transport coherence can also be experimentally determined.

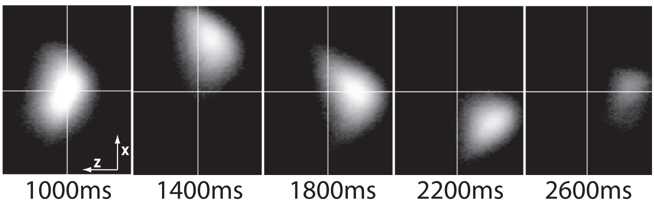

Figure 1: *Selected images from a single run of our Brownian motor with several directional shifts. The atoms are first held for 1000ms before a drift upwards is introduced. 400 ms later the drift is reversed for 800ms until it is reverses again for the final 400ms.*

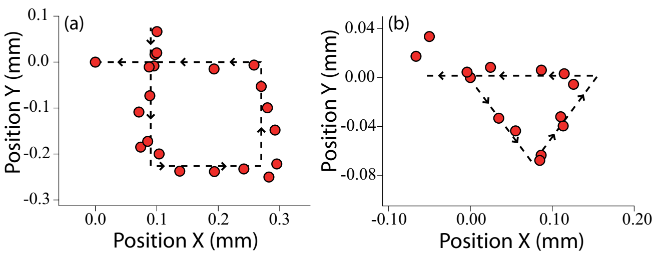

Figure 2: *Drifts along predesigned paths are demonstrated for (a) a square and (b) a triangle. The step time between each point is 60ms.*

Gutzwiller Analysis on Bose-Fermi Mixtures of Ytterbium isotopes in an Optical Lattice

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Mixtures of bosonic and fermionic atoms in an optical lattice exhibit novel many-body phenomena induced by the interplay between quantum statistics and atomic interactions. For instance, in a mixture of bosonic ^{87}Rb and fermionic ^{40}K atoms, it was observed that the coherence of bosons is highly reduced by the strong interactions between both atomic species[1].

Recently, Bose-Fermi mixtures consisting of different Yb isotopes have been investigated extensively[2]. In these systems, the mass of fermionic and bosonic atoms are almost equal to each other, which realizes the ideal situations for investigating the many-body effects purely. Furthermore, a high-resolution spectroscopy using ultranarrow transitions in Yb atoms provides us with the precise information on the atomic interactions. These outstanding features of Yb make it possible to quantitatively compare the experimental results to the theoretical calculations.

We numerically study the Bose-Fermi mixtures of Yb isotopes trapped in the three dimensional optical lattice. Using Guztwiller approximation, we carry out quantitative simulations at finite temperatures. We investigate two types of mixtures: (i) a mixture of ^{170}Yb and ^{173}Yb with the attractive boson-fermion interaction, and (ii) a mixture of ^{174}Yb and ^{173}Yb with the repulsive boson-fermion interaction. We calculate various experimentally observed quantities. For example, the number of doubly-occupied lattice sites can be measured via the photoassociation spectroscopy. This measurement is very sensitive to the Mott transition. By comparing the numerical and the experimental results, we clarify the role of boson-fermion interactions in the Mott transitions of the attractive and repulsive Bose-Fermi mixtures. In addition, by systematic calculations at finite temperatures, we discuss heating or cooling of atomic samples during the lattice ramp up in our systems.

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Mechanical properties of propagation invariant beams and their effect in cold atoms

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The generation of optical fields that maintain their transverse structure over long distances has increased the interest in their theoretical and experimental study. Explicit expressions are known for four symmetries: rectangular (plane waves), circular (Bessel waves), elliptic (Mathieu waves) and parabolic (Weber waves). It is well known that the mechanical variable directly associated to plane waves is the linear momentum. The photons associated to Bessel waves can carry a well defined orbital angular momentum. In this work, explicit expressions are given for the mechanical properties of Mathieu and Weber electromagnetic fields [1]. The density of these mechanical variables are shown to be given by products of second order derivatives of the electric and magnetic fields of the wave and can be interpreted as densities of products of linear and angular momenta.

The possibility that these mechanical properties can be transfered to cold atoms in optical lattices built from these structured beams is numerically explored [1,2]. We concentrate on the quasi conservative red detuned far-off-resonance regime. We also show that the atoms dynamics in this structured lattices is non trivial. The system exhibits quasi periodic and chaotic behaviors which can be controlled by varying the intensity of the beams. The presence of Levy-like flights on the transverse plane of the lattice, as well as the spectral density of the trajectories are used as chaos signatures. Finally we propose a scheme to split a cloud of thermal atoms using a Weber beam [3].

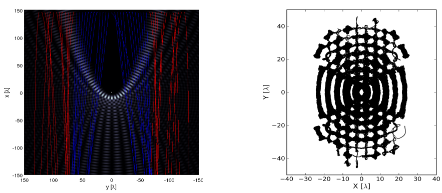

Figure 1: *(a)A thermal atom cloud of atoms impinging on a high order Weber beam; (b)An example of the most common behavior of a chaotic trajectory of a single atom in a TE zero-th order Weber optical lattice.*

[1]B. M. Rodríguez-Lara, R. Jáuregui, Phys. Rev. A 78, 033813 (2008); B.M. Rodríıguez-Lara , R. Jáuregui, Phys. Rev. A 79, 055806 (2009)

[2]K. Volke-Sepúlveda, R. Jáuregui, J. of Phys.B-Atomic Molecular and optical Phys. 42, 085303 (2009)

[3]B. M. Rodríguez-Lara, R. Jáuregui, Phys. Rev. A 80, 011813 (2009)

Tunneling effect observed in the resonance fluorescence spectrum of a single atom in a Lamb-Dicke regime

J-R. Kim[1], W. Kim[1], C. Park[1], S. Kang[1], S. Lim[1], J. Kim[2], J. Ihm[1], and K. An[1]

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Recent progresses in experimental technique of trapping neutral atoms in an optical lattice have drawn much attention for possible applications to quantum information, quantum simulation, quantum communication, etc. In many experiments, a magneto-optical trap(MOT) serves as a basic tool-kit for loading atoms into optical lattice. It has been reported that cold atoms trapped in a phase-stabilized MOT itself can also be localized in sub-wavelength-scale regions[1]. In our experiment, we trapped a single atom[2] in such an optical lattice-like potential and observed resonance fluorescence spectrum from the atom localized in a Lamb-Dicke regime. To measure the spectrum of such a weak signal, we used the photon-counting-based second-order correlation spectroscopy (PCSOCS)[3]. Measured spectrum was composed of a central Rayleigh peak and two Raman sidebands.[4] For a quantitative understanding of the linewidth of the Rayleigh peak we introduced a single-particle band theory describing a matter-wave tunneling between adjacent micro-potential wells. The observed lineshape was well fit by a Voigt profile and the observed linewidths were in good agreement with the prediction by the band theory including relevant level lifetime broadening as summarized in Fig. 1.

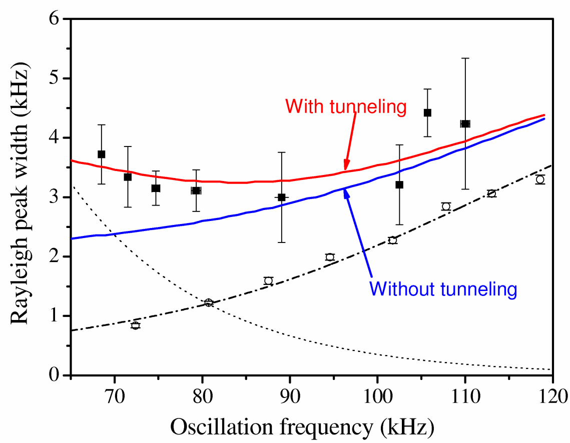

Figure 1: *Observed linewidths of the central Rayleigh peak as trap oscillation frequency.*

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[4]C. I. Westbrook et al., Phys. Rev. Lett. 65, 33 (1990)

Semi-symmetric molecules and their symmetry operations with Clifford algebra

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The Clifford algebra produces the new fields of view in the atom and mathematical physics, definition of bodies and rearranging for equations of mathematics and physics. The new mathematical approaches play an important role in the progress of physics. After presenting Clifford algebra and quaternions, the symmetry operations in molecular physics with Clifford algebra and quaternions are defined. This symmetry operations are applied to some symmetric and semi-symmetric solids. Also, the vertices of some symmetric semi-symmetric solids presented in the Cartesian coordinates are calculated.

Position of Muonic Molecular Resonances in Hydrogen Multilayer

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To study of kinetics of $\mu t_{1s}(E)$-muonic atoms in the hydrogen multilayer target $H/T \oplus D_2$, coupled one-dimensional transport and rate equations are written and solved by implicit method. The structure of present multilayer has been cooled to 3 K and it includes only a small concentration of tritium($c_{T_2} \approx c_t \approx 10^{-3}$). As before, multilayer target was used without attention to the μt-transport [1]. Here, the contribution of molecular resonances of the complex $[(dt\mu)_{J\nu}dee]^*_{Kv}$ is fully taken into account. $J\nu(Kv)$ are ro-vibrational quantum numbers of the $dt\mu$ ion(complex). The present work shows that these molecules are significantly formed in the collision energy $E \simeq 0.47\ eV$ and $x \simeq 3.065(\mu m)$, where x denotes the vertical distance measured from H/T layer(see Fig. 1). For duration times, the results of the population of $\mu t_{1s}(0.47\ eV)$ atoms are plotted versus $X(X \equiv x - 2.9)$, as shown in Fig. 1. By using time step sizes less than mean duration time of muonic atom formation and space-grid points more than $n_{g.p.} = 2000$, the method is numerically stable. The present structure can operate as a source of μt atomic beam. For more information, $\mu t_{nl\geq 2s}$ atoms can form the complex more in gas targets [2].

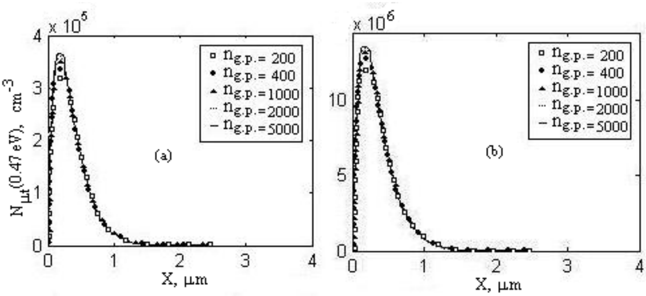

Figure 1: *The population of muonic atoms in $x \simeq 3.065\mu m$ is maximum. The results of the population versus X in the duration times $\simeq 10^{-8}$ s (a) and 10^{-9} s (b), by using different numbers of space grid points. The muon beam has intensity of about 10^8 muons/s, $N_\mu(x = 0, t = 0)$.*

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