Rydberg's cat: creating giant polyatomic molecules

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It has been proposed that a Rydberg electron interacting via the zero-range Fermi pseudopotential with a nearby perturbing atom could bind into ultralong range Rydberg molecular states[1]. An experiment with ultracold Rydberg atoms in a dense rubidium magneto-optical trap (MOT) recently realized the existence of the istotropic utralong range Rydberg molecules[2].

We predict the existence of a class of ultralong range macroscopic Rydberg molecules which can be created in ultracold traps from a polar molecule and a Rydberg atom[3]. The molecular binding is due to the long range anisotropic interaction of the Rydberg electron with the permanent dipole of the trapped polar molecule. These giant molecules have deep binding energies, $E_b \simeq 20$ GHz, are ultralong range, $R \simeq 2000\ a_0$, and are well protected from the non-adiabatic avoided crossings, which could lead to their premature demise. A double-well structure, shown in Fig. 1(left), arrises in which the orientation of the polar molecule dipole, d, is controlled by the Rydberg electron, as shown schematically in Fig. 1(right).

The lowest vibrational levels in L (0_L) and R (0_R) wells in Fig. 1 (left) can be coherently coupled via a microwave Raman transition. The on-resonance, but weak intensity two-photon transition, via an intermediate vibrational state (v_R) in the extended right well efficiently transfers population between different electronic states. The configurations in the L and R wells, respectively, are with the molecular dipole pointing toward or away from the ionic core. The coherent Raman scheme ensures that the molecular dipole orientations become entangled. The dipolar interaction of two polarized giant Rydberg molecules could be coupled to the internal superposition states of the polar molecules.

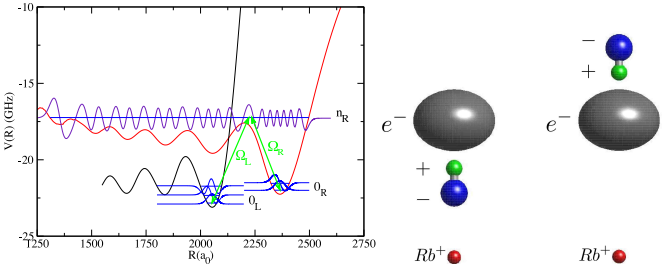

Figure 1: *Left: The two lowest Born-Oppenheimer potentials are shown with several bound state wavefunctions. A proposed coherent Raman transition between the two wells is also shown. Right: A schematic illustration of the available molecular configurations is shown.*

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Vortex Lattices in Dipolar Spin-1 Bose-Einstein Condensates

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Dipolar quantum gases have attracted significant interest in the recent years[1]. Exploring beyond semiclassical spin models[2,3], we have calculated phase diagrams for spin-1 Bose-Einstein condensates in the presence of long-range dipole-dipole interactions in the parameter space spanned by the angular rotation frequency of the system and the relative dipolar coupling strength. Variety of spin textures emerge in these systems including magnetic crystals and vortex sheets induced by dipolar interactions. On changing the rotation frequency and the dipolar coupling strength, transitions between different types of textures take place. Figure 1(a) shows a rhombic half-quantum vortex lattice obtained for antiferromagnetic spin-exchange interaction while the square skyrmion lattice texture in Fig 1 (b) results due to the ferromagnetic spin-exchange interaction.

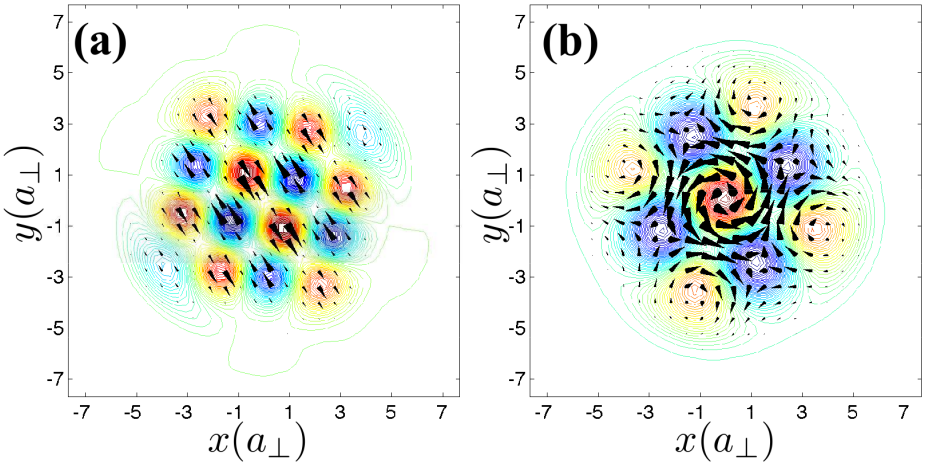

Figure 1: *Spin textures in dipolar spin-1 Bose-Einstein condensates for (a) antiferromagnetic- (b) ferromagnetic spin-exchange interaction. Both states shown rotate at angular frequency of 0.4 times the radial harmonic trapping frequency. The arrows are plotted using the x- and y-components of the local spin and the contour lines illustrate the x-component (a) and z-component (b) of the spin density.*

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A slow and cold beam of YbF molecules

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A cold, slow source of molecules is of interest for various fields in physics and chemistry. These include high resolution spectroscopy [1], quantum information processing [2] and fundamental physics tests such as the measurement of the electric dipole moment of the electron [3]. Especially for the latter, a high flux source of cold molecules is advantageous [4].

As laser cooling is not applicable for most molecules due to their complex internal structure, other ways to cool them have to be sought. One approach is buffer gas cooling, where the molecules reach temperatures down to a few Kelvin by colliding with a cold buffer gas[5]. Using this method we report the production of a cold, slow beam of YbF molecules. Using laser induced fluorescence on the A $^2\Pi_{1/2} \leftarrow$X$^2\Sigma^+_{1/2}$ transition, we measure a molecular beam flux out of our buffer gas cell of a few 10^{11} molecules sr^{-1}s^{-1} in the ground vibrational and rotational state. The temperature of this beam was measured to be 4.1 ± 0.6 K. By looking at the time of flight profiles on two photomultiplier tubes 109mm apart, the centre of mass velocity was found to be 160 ms^{-1}. Comparing these beam parameters to conventional supersonic sources [6] shows that our beam flux is ten times higher and the molecules travel about four times slower. We plan to use this intense, slow beam of molecules to improve the sensitivity of our existing electron edm experiment.

By working with different buffer gas densities and trading off beam flux with forward velocity, we are able to tune the centre of mass velocity of the beam from a few tens of ms^{-1} in the effusive flow regime up to hundreds of ms^{-1} for hydrodynamic flow. These low velocities offer the possibility of loading the molecules directly into a trap, where further cooling such as sympathetic cooling, laser cooling or evaporative cooling can be applied.

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Sympathetic cooling of trapped polar molecules with ultracold atoms: results of trajectory simulations

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We present numerical simulations showing the sympathetic cooling of polar molecules using ultracold atoms. An ensemble of initially warm molecules evolves within a trap, each having occasional elastic collisions with a distribution of ultracold atoms. By solving the motion of many individual molecules, the ensemble properties of the cloud can be deduced. The deepest traps for molecules work only for weak-field seeking states, but in these states the molecules are vulnerable to inelastic collisions that change the rotational state, resulting in ejection from the trap. We focus instead on traps for ground state molecules which are immune to inelastic collisions because the collision energy is too low to excite them out of the ground state. In particular, we study sympathetic cooling in two types of trap suitable for confining ground state molecules - a microwave trap[1] and an ac electric trap[2]. We will present results showing how the molecule temperature and survival probability depend on the trap geometry and on the spatial distribution, the density and the temperature of the ultracold atoms. This work is part of a larger experimental program to sympathetically cool molecules using ultracold atoms.

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Supersolid Phase of Polar Molecules in a Continuous Space

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A supersolid phase of bosonic polar molecules loaded in a 2D continuous system (i.e. without optical lattice potential) is predicted. The crystal order is found to be stabilized by the potential minimum of the inter-particle interaction, which can be detuned in a wide parameter regime by applying external AC field. We numerically and analytically calculate the full scattering amplitudes and vertex function, giving a promising meafield description of such supersolid phase. The phase diagram is also studied in different external field.

Interaction-induced ferroelectricity in the rotational states of polar molecules

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We show that a ferroelectric quantum phase transition can be driven by the dipolar interaction of polar molecules in the presence a microwave field. The obtained ferroelectricity crucially depends on the harmonic confinement potential, and the macroscopic dipole moment persists even when the external field is turned off adiabatically. The transition is shown to be second order for fermions and for bosons of a smaller permanent dipole moment, but is first order for bosons of a larger moment. Our results suggest the possibility of manipulating the microscopic rotational state of polar molecules by tuning the trap's aspect ratio (and other mesoscopic parameters), even though the later's energy scale is smaller than the former's by six orders of magnitude.

Stability of Superflow in Supersolid Phases of Dipolar Bose Gases in Moving Optical Lattices

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We investigate the stability of superflow of dipolar Bose gases[1] in a two-dimensional optical lattice. Assuming that the dipole moments are polarized to the direction perpendicular to the lattice plane, we consider here the case of the isotropic dipole-dipole interactions. This system is of particular interest because recent quantum Monte Carlo (QMC) simulations have shown that the isotropic long-range interactions stabilize the so-called supersolid (SS) phase, which is characterized by the coexistence of crystalline long-range order and superfluidity, in a two-dimensional Bose-Hubbard system[2].

In experiments of ultracold gases, while the existence of the crystalline orders can be identified by using the Bragg scattering techniques[3], it is difficult to measure directly the superfluid fraction. In this work, we propose that the superfluidity of the SS phases can be identified by measuring the critical velocity above which superflow breaks down. First, we discuss why the long-range interactions stabilize the SS phases. We then perform linear stability analyses for the dipolar Bose-Hubbard model in the hardcore boson limit[4], and show that the superflow can exist unless the velocity exceeds a certain critical value, not only in the standard superfluid phase but also in the supersolid phase. Additionally, we show that the critical velocity in the supersolid phase is remarkably smaller than that in the superfluid phase, and that there exists a parameter range in which the SS phases are stabilized by a finite superflow. We also discuss the influence of quantum fluctuations on these results within the cluster mean-field approximation.

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Realizing Dipolar Chain Liquid of Polar Molecules in 3D Optical Lattices

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Recent experimental progress on ultra-cold polar molecules opens new realms to explore intriguing quantum phase with dipolar interaction. One of possible phenomena is self-assembled chain liquid in a stack of strongly confined pancake traps. It is, however, not easy for polar molecules to form a spontaneous chain liquid due to lack of binding mechanism. Here, we propose an adiabatic process in formation of chain liquids with a presence of a 3D optical lattice. That is, polar molecules are first tightly trapped in a 3D optical lattice. The electric field is then tuned on to enhance the chaining process (due to the localized position of each molecules), and then a free moving chain can be formed by relaxing the in-plane lattice potential adiabatically. Our studies further provide the theoretical criteria for realizing other composite particles with polar molecules.

Off-axis Vortex in a Rotating Dipolar Bose-Einstein Condensation

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We consider a singly quantized off-axis straight vortex in a rotating dipolar ultracold gas in the Thomas-Fermi (TF) regime. We derive analytic results for small displacements and perform numerical calculations for large displacement within the TF regime. We prove that the dipolar interaction energy increases (decreases) as the vortex moves from the trap center to the edge in an oblate (a prolate) trap. We show that the angular velocity representing the onset of metastability is lowered (raised) in an oblate (a prolate) trap. We find that the effect of the dipole-dipole interaction is to lower (raise) the precession velocity of an off-center straight vortex line in an oblate (a prolate) trap.

Cold Atom Temperature Measurements using an Optical Nanofibre

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In order to characterise and probe cold atoms, it is desirable to implement a detection system which is robust, non-destructive and highly-sensitive. Recently, it has been shown that the characteristics of cold, neutral atoms can be analysed using optical nanofibres.[1] These are extremely thin, dielectric waveguides fabricated from commercially-available optical fibre. If a nanofibre is placed in close proximity to a light source, there is a finite probability that the external photons will be coupled into the nanofibre. A photon counting device can be used to detect these coupled photons. In this work, we use the method of forced oscillations to calculate the temperature of a cold cloud of ^{85}Rb atoms using a nanofibre.

Rb atoms are laser-cooled and trapped in a standard magneto-optical trap (MOT) setup. We apply a spatial sinusoidal variation to the centre of the MOT. We then monitor the frequency response of the phase between the motion of the oscillating trap and the cloud of Rb atoms by coupling the fluorescence from the cold atoms into the guided mode of the nanofibre and monitoring the photon count rate. We measure temperatures below the Doppler limit and find the expected behaviour for temperature versus detuning. Our studies demonstrate the sensitivity of the optical nanofibre to very small numbers of atoms which allows us to make realistic measurements of many fundamental MOT characteristics.

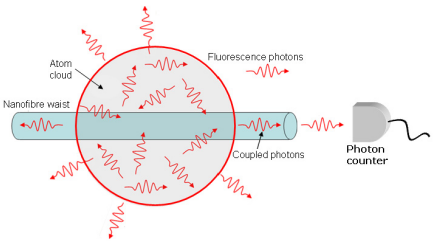

Figure 1: *Schematic representation of a passive optical nanofibre probe.*

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RF evaporative cooling in a resonant RF-dressed trap

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Adiabatic potentials for ultracold atoms, resulting from the radiofrequency (RF) dressing of atoms in a inhomogeneous magnetic field[1], have been demonstrated[2] and are used by many groups to propose and realize unconventional traps, in particular in the framework of atom chips[3]. These RF-dressed traps are usually loaded directly from a conventional magnetic trap, by ramping up the RF amplitude or sweeping the RF frequency.

In the 'non-resonant configuration', the adiabatic potential results essentially from a light shift induced by a variation of the RF coupling strength. On the other hand, the trapping potential may be due essentially to the variation of the RF detuning, the atoms being then attracted towards the regions of zero detuning[1]. In this 'resonant configuration', the atoms sit at points where the RF field is resonant with the magnetic level spacing, which makes them more sensitive to fluctuations of the RF frequency[4]. In particular, the transfer of the atoms from the initial magnetic trap to the RF-dressed trap is not usually adiabatic, which results in an initial heating in the loading phase and the destruction of the condensate[2,5]. A better strategy is then to load thermal atoms in the dressed trap, and cool them further by RF evaporative cooling in the RF-dressed trap with a second, weak, RF field. We present experimental results of RF spectroscopy and RF evaporative cooling in trap operating in the resonant configuration[6]. We discuss the position of the expected lines and the strength of the second RF coupling.

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A New Method for Producing Ultracold Molecular Ions

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Because molecular ions are easily trapped for many minutes, there are possibilities for cooling and interrogation that are not applicable to neutral molecules. Furthermore, because ion trapping is species independent, many of the major goals of cold polar molecule physics can be realized with ions. The most noteworthy of these goals include the study of cold chemistry, which not only has important implications for understanding the formation of interstellar clouds[1], but will allow for investigation, and possible control, of reactive collisions in the quantum regime[2]; precision measurement of molecular transitions, which can be used to very sensitively measure parity violating effects[3]; and the implementation of a scalable quantum computation architecture[4].

To date, cooling of molecular ions has been demonstrated through sympathetic cooling collisions with both cold helium buffer gas[5] and laser-cooled atomic ions[6]. Unfortunately, neither of these methods simultaneously produce both ultracold and internal ground-state molecules, *i.e.*, the ground state in both the internal and external degrees of freedom. Sympathetic cooling with atomic ions efficiently cools the translational temperature of the molecular ions, but the long range collisions prevent the atomic ions from efficiently coupling to the internal degrees of freedom of the molecular ions. By contrast, buffer gas cooling has been shown to cool the internal degrees of freedom of molecular ions, but due to the low polarizability of the noble gas atoms used, the process is inefficient and in general leaves the molecules at a higher translational temperature than is usually desired. More sophisticated cooling schemes have recently been implemented to circumvent these shortcomings[7,8], resulting in cooling of the rotational degree of freedom to $\sim$20 K.

We present a general method to produce ultracold, internal ground state molecular ions by sympathetical cooling with neutral, laser-cooled atoms[9]. This method is expected to be more efficient than the methods mentioned above because the laser-cooled neutral atoms have a relatively high polarizability and the collisions are short range. Recent data on our experiments which co-trap $BaCl^+$ ions in a linear quadrupole trap with ultracold Ca atoms in a magneto-optical trap are presented. Preliminary data shows that the chemical reaction rate constant, κ, of the $BaCl^+$ ions with the ultracold Ca atoms to be $\kappa < 10^{-11}$ cm^3/s.

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Cross Phase Modulation with Group-Velocity-Matched Double Slow Light Pulses

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We present the experimental studies on the cross phase modulation between two weak slow light pulses with group velocity matching by the double electromagnetically induced transparency (EIT) in cold cesium atoms. The double EIT is implemented with two coupling fields that drive the F=3→ F'=3 and F=4→ F'=4 transitions (coupling 1 and 2) and two probe fields that drive the F=4→ F'=3 and F=3→F'=4 transitions (probe and signal) of the D_2 line of cesium. The cross phase modulation between the two probe pulses is obtained through the asymmetric M-type system by introducing a two-photon detuning in one of the EIT system or by adding a small magnetic field while keeping both EIT systems at two-photon resonance. With a two-dimensional magneto-optical trap operated in the temporal dark MOT mode, the optical densities for both probes can be higher than 75. By tuning either one of the intensity of the coupling field, the group velocity matching for the probe and signal pulses can be obtained. Using the beat-note interferometer, we dynamically measure the cross phase shift of the probe pulse introduced by signal. With a signal Gaussian pulse of a 4-μs FWHM duration and a peak power of 20nW focused to a waist of 37 μm (corresponding to a Rabi frequency of 0.4Γ), the peak cross phase shift on the probe pulse is measured to be 0.55 radian.

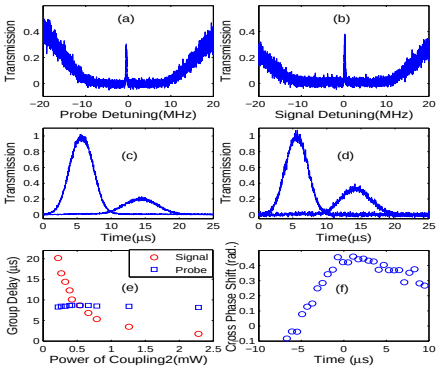

Figure 1: *(a)(b) The typical EIT spectrum for probe and signal.(c)(d) The typical slow light pulses and reference pulses for probe and signal. (e)The group delays for probe and signal versus the intensity of coupling 2. (f) The typical cross phas shift among the probe pulse. t=0 is the center of the probe pulse.The group delays for probe and signal are 7 μs and the two-photon detuning for signal is -80kHz in this case.*

Laser cooling of atoms by collisional redistribution of fluorescence

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The general idea that optical radiation may cool matter was put forward by Pringsheim already in 1929 [1]. Doppler cooling of dilute atomic gases is an extremely successful application of this concept, and more recently anti-Stokes fluorescence cooling in multilevel systems has been explored in solids. Collisional redistribution of fluorescence is a proposed different cooling mechanism that involves atomic two-level systems [2], though experimental investigations in gases with moderate density have not reached the cooling regime. We have experimentally demonstrated cooling of an atomic gas based on collisional redistribution of fluorescence, using rubidium atoms subject to 200 bar of argon gas pressure [3]. The frequent collisions in the ultradense gas transiently shift a far red detuned laser beam into resonance, while spontaneous decay occurs close to the unperturbed atomic resonance frequency. During each excitation cycle, a kinetic energy of order of the thermal energy $k_B T$ is extracted from the dense atomic sample. We presently achieve cooling in a heated gas from an initial temperature of 410°C down to -120°C temperature in the laser beam focus[4]. The cooled gas has a density of more than 10 orders of magnitude above the typical values in Doppler cooling experiments. Future prospects of the demonstrated technique can include cryocoolers and the study of homogeneous nucleation in saturated vapour.

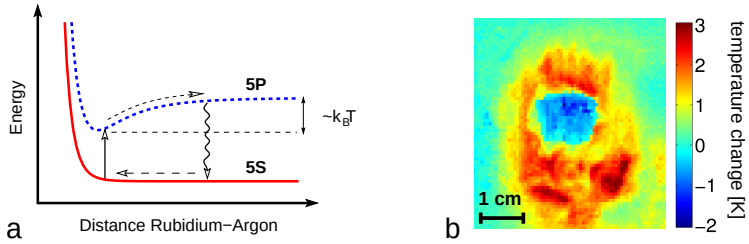

Figure 1: *(a) Simplified scheme of rubidium energy levels during collisions with a buffer gas atom and the cycle of laser cooling by collisional redistribution. Strongly red detuned photons can be absorbed, when a perturber atom approaches the rubidium atom. Reemission is most probable for unperturbed atoms. (b) Indirect cooling of the sapphire cell window. The gas behind the window is cooled by laser radiation. The remnant of the temperature drop can be detected with a standard IR-camera as change in the blackbody spectrum of the sapphire window, visible in the image center.*

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Magneto-Optical Trapping of Neutral Mercury

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Neutral mercury offers numerous opportunities for experiments in cold atomic and molecular physics ranging from high precision measurements[1], e.g. an optical lattice clock, to the formation of ultracold molecules by photoassociation[2].

The 253.7-nm $^1S_0$-$^3P_1$ trapping transition has a saturation intensity of $10.2\,\mathrm{mW/cm^2}$, with a natural linewidth of $1.27\,\mathrm{MHz}$. Since the ground state is free of fine- and hyperfine structure cooling on this line constitutes a closed transition. Consequently, no additional repumping laser is required. Our trapping laser is based on a narrow, detuned single-mode and single-frequency Yb:YAG disc laser with a continuous output power of up to $5\,\mathrm{W}$ at the required wavelength of $1014.9\,\mathrm{nm}$. Up to $280\,\mathrm{mW}$ at the desired wavelength of $253.7\,\mathrm{nm}$ are provided by frequency quadrupling employing two frequency doubling cavities. The laser is stabilized by saturation spectroscopy to a Hg-Cell at room temperature. The Hg-reservoir attached to the vacuum chamber can be varied between -70° and -10°C. During experiments the reservoir temperatures is set between -40°C and -24°C.

The characterization of our magneto-optical trap was performed by analysis of fluorescence images of the captured atomic clouds recorded by a UV-enhanced EMCCD camera. Currently, we trap up to $(3.2 \pm 0.3) \times 10^6$ of bosonic ^{202}Hg-atoms. The average $1/e^2$ cloud radius was measured to be $(251 \pm 17)\,\mu$m corresponding to a density of $(4.8 \pm 1.4) \times 10^{10}$atoms/cm^3. The lifetime in the trap was measured to $(1.03 \pm 0.09)\,s$ with a capture rate of $(1.94 \pm 0.12) \times 10^6\,\mathrm{s}^{-1}$. We have also trapped approx. 8.2×10^5 atoms of the fermionic isotope ^{199}Hg (c.f. fig. 1a). We determined the temperature of the cloud to approx. 300 μK limited by the quality of the laser lock.

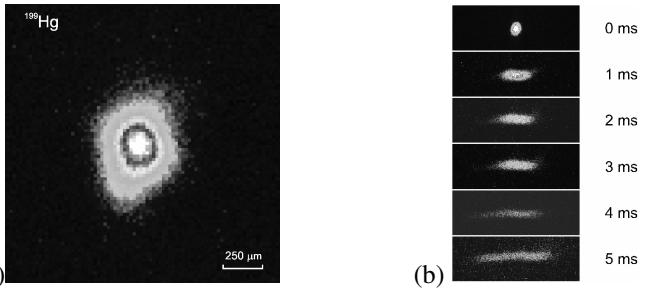

Figure 1: *(a) Cloud of trapped ^{199}Hg-atoms recorded using an EMCCD-camera. (b) Ttime-of-flight images of the expansion of a ^{202}Hg cloud. False color intensity scaling varies for different times.*

[1] H. Hachisu, et al., "Trapping of neutral mercury atoms and prospects for optical lattice clocks", Phys. Rev. Lett. **100**, 053001 (2008)

[2] T. Walther, "Prospects of trapping neutral mercury", J. Mod. Opt. **54**, 2523 (2007)

Laser System for Laser Cooling Relativistic Ion Beams and Dipole Traps

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TU Darmstadt, Institute for Applied Physics, D-64289 Darmstadt, Germany

The generation of ultra-cold relativistic ion-beams in storage rings is of great interest[1], e.g. for precision measurements in atomic physics. Therefore, we are setting up an all-solid state laser system providing quickly tunable radiation at the Ar^+ ion laser wavelength of 514 nm.

The laser system consists of an home-built external cavity diode laser (ECDL), an Yb-doped fiber amplifier and the second harmonic generation (SHG) unit. The ECDL follows the design by Kaminski[2] and is equipped with a high-performance laser diode at 1028 nm providing up to 220 mW of output power. This radiation is used to seed a fiber amplifier consisting of an Yb-doped, polarization maintaining fiber. Finally, the SHG unit with an external build-up cavity completes a tunable replacement for an Ar^+-ion laser at 514 nm. The mode-hop free tuning range of the ECDL of 26 GHz at a repetition rate of up to 200 Hz is achieved by a locking technique based on polarization spectroscopy[3]. The fiber amplifier produces a fundamental output power of up to 10 W in the current configuration. Currently, we are setting up the SHG unit.

Due to the high stability, narrow-linewidth, all-solid state character we expect this laser system, either with or without the frequency doubling stage, to be useful in a variety of other applications as well such as setups for dipole traps, optical lattices, or pumping Ti:Sapphire lasers etc.

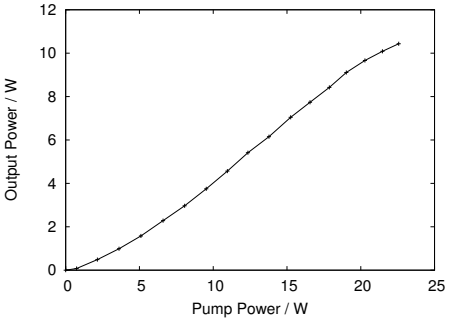

Figure 1: *Power characteristics of the fiber amplifier at 1028 nm.*

[1] M. Bussmann et al., "All-optical Ion Beam Cooling and Online Diagnostics at Relativistic Energies", Proc. of COOL09, (2009)

[2] J. Hult et al., "Wide-bandwidth mode-hop-free tuning of extended-cavity GaN diode lasers", Appl. Opt. 44, 3675 (2007)

[3] Thorsten Führer et al., Actively Controlled Tuning of an External Cavity Diode Laser by Polarization Spectroscopy, Opt. Express 17, 4991-4996 (2009)

The external chip economically manufactured : Toward the condensation

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We manufactured economic atom chip which is separated from vacuum chamber by dielectric mirror, external type, in 26 mm $\times$ 26 mm size. The Al plate was used as a substrate of chip for high thermal conductivity, strong resistance to physical impact, and readily supply of electric power. And then we printed some useful Cu wires as Figure 1 (a) for making the ultra cold atoms. By using the vacuum cell in 18 mm $\times$ 18 mm $\times$ 70 mm size constructed like Figure 1 (b) with the chip, Rb atoms were magnetically optical trapped below the mirror surface, mirror-MOT [1], and the atomic cloud is retrapped by the U shaped wire on the chip [2]. As generally knowing the Z shaped wire and homogeneous field can make the Ioffe-Pritchard type trap and we are trying to magnetically trap Rb atoms using our chip. Our external type of metal chip is a good candidate for more applicative and economic system making ultracold atoms.

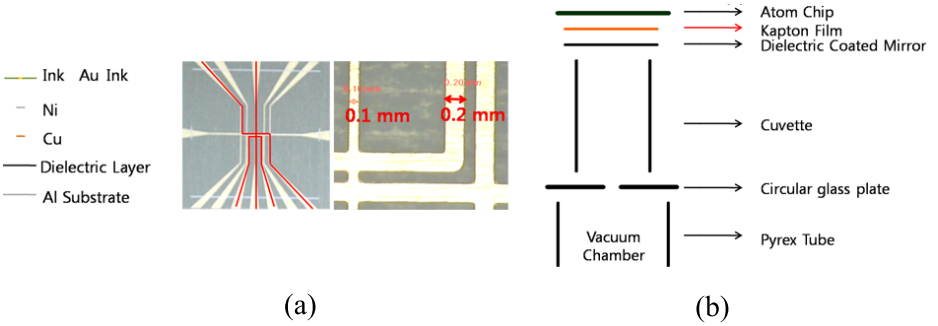

Figure 1: *Constructions of chip and vacuum cell (a) The widths of the U and the Z-type Cu wires are 200 μm, and that of the single linear wire is 100 μm. The thicknesses of the wires are approximately 15 μm. The horizontal wire is for evaporation cooling, (b) Construction of a vacuum cell with an external atom chip. The thickness of the Kapton film is approximately a few hundred μm.*

[1] H. Yu, L. Lee, K. H. Lee, J. B. Kim, "A magneto optical trap below a dielectric coated mirror surface", J. Opt. Soc. of Korea 13. 223.(2009)

[2] H. Yu, K. D. Jang, J. D. Kim, L. Lee, J. B. Kim,"Transference of cold ^{85}Rb atoms from a mirror MOT to an U-MOT on an external atom chip", J. Korea Phys. Soc. 56. 770.(2010)

Trapping a single neutral atom in a blue detuned optical bottle beam trap

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We demonstrated trapping a single rubidium atom in a blue detuned optical bottle beam trap.By strongly focusing a blue detuned optical bottle beam generated by a spatial light modulator (SLM), we were able to efficiently capture and store a ^{87}Rb atom. Under typical experimental conditions, the lifetime of the atoms in the trap is as long as several seconds, which is comparable with the bright trap and long enough for next step experimental requirement.

Dark traps for single atoms have been realized in a cavity[1] or in optical lattices[2]. In our experiment, we choose strongly focusing a blue detuned laser optical bottle beam generated by an SLM to trap a single ^{87}Rb atom. Comparing with other blue detuned optical traps for single atoms[1,2], this dark trap possesses advantages of both scalability and addressability, also the trapped atoms can be transported freely in space by well controlled movement of the optical trap.

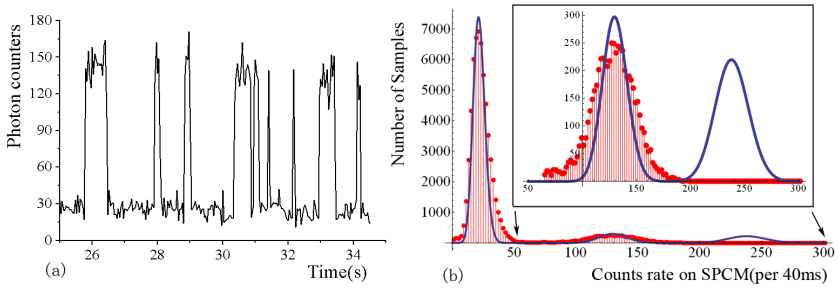

Figure 1: *(a)Number of photons counted by a single photon counting module(SPCM) with 40ms time bins, (b)Histogram of photon counting data lasting for 2600s (red dots) and the fit with a compound Poisson law for the 0-atom,1-atom and 2-atom peaks(blue line).*

[1]T. Puppe, I. Schuster, A. Grothe, A. Kubanek, K. Murr, P. W. H. Pinkse, and G. Rempe, Phys. Rev. Lett **99**, 013002 (2007).
[2]K. D. Nelson, X. Li and D. S. Weiss, Nature Phys. **3,** 556(2007).

Magnetic traps designed with type-II superconducting strips in the remanent state

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[3]*Department of Physics and Astronomy, Rowan University, New Jersey, USA*

We design novel magnetic traps for neutral atoms based on the average magnetic fields of vortices trapped in type-II superconducting strips. We demonstrate a few types of these vortex-based atom traps, such as quadrupole traps, double traps and self-consistant traps without any applied bias fields, in details[1]. The vortices can be induced in a type-II superconducting strip by an external magnetic field pulse perpendicular to the surface or a transport-current pulse. We study the both cases. The average field of the vortices can be computed through the mesoscopic induced supercurrents. We use Bean's critical state model to study the induced supercurrent density distributions and compute the spacial imhomogeneous magnetic field by the Biot-Savart theorem. Together with bias fields, we may obtain a magnetic field minimum to trap low-field seeking atoms. For comparison, we also demonstrate the analogous magnetic traps generated by normally conducting wires. The vortex-based traps are expected to reduce the technical noise, because of the absence of the transport-currents.

Due to the memory effect of the type-II superconductors, various vortex patterns can be obtained by flexible loading-field and transport-current sequences. The resulting variable magnetic fields are employed to make versatile trapping potentials.

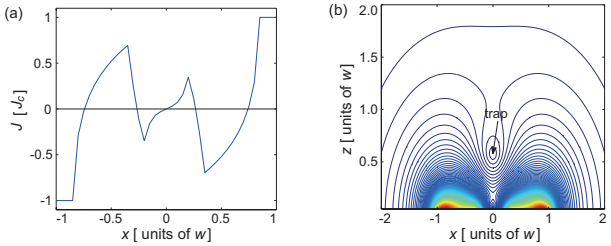

Figure 1: *A typical self-sufficient trap. (a) the induced supercurrent density distribution. (b) the magnetic field configuration.*

Fig.1 shows a typical self-sufficient trap without any bias fields. The absence of the bias fields may further reduced the technical noise and make this kind of trap convenient to be integrated with other devices. On the other hand, these vortex-based traps are strongly dependent on the the vortex distribution, so they may be used as sensitive probe of the distribution and dynamics of the vortices in the superconductors.

[1]B. Zhang, R. Fermani, T. Müller, M.J. Lim, R. Dumke, "Design of magnetic traps for neutral atoms with vortices in type-II superconducting microstructures"

Optical Double-well Array Based on Binary Optics Method

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We demonstrated how to generate optical double-well traps array based with binary optics elements and optical fiber bundles . Using a home-designed focusing objective with a numerical aperture of 0.38, we produced a far-off-resonance optical dipole trap (FORT) with waist of the FORT beam of about $3.4\pm0.2\mu$m. We inserted a Dammann grating to the corresponding position of the setup (Fig.1(a)). The Dammann grating split the FORT beam into several beams of equal intensity and each beam generated a micro-optical trap on the focal plane. We used two fibers to form two sets of optical traps array. Then we adjusted the inclination between the row of fibers facing and grooves of the grating and made the two set of traps array to become a double-well trap array. We have observed a one-dimensional atom array and a double atom array (Fig.1(b)(c)).

Using another method, we generated double-well traps along the direction of propagation of the trapping laser. When a Gaussian beam passes through a two-zone -phase plate and then is focused by an objective with large numerical aperture, double-well traps will be formed near the focal plane. The distance between two wells depends on the numerical aperture of the objective lens and the width of the laser beam. In addition, a hollow trap can be produced with blue-detuned incident lasers. We have realized capture of atoms in this kind of traps.

Our method can be use to build scalable quantum logic network[1]. It also can be applied to the study of dynamics of Bose-Einstein condensates in a multi-wells potential[2].

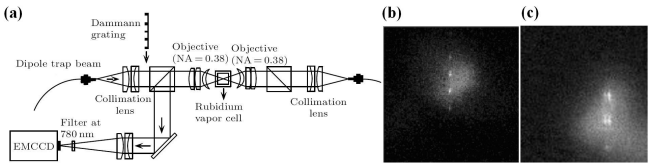

Figure 1: *(a)Schematic of the experimental apparatus. The Dammann grating could be inserted into the marked position. (b)EMCCD image of atoms in the one-dimensional micro-optical trap array. (c)EMCCD image of atoms in the double-well trap array.*

[1]L. Isenhower, M. Saffman, et. al., "Demonstration of a Neutral Atom Controlled-NOT Quantum Gate.", Phys. Rev. Lett. **104**, 010503 (2010).

[2]B. Liu, L. B. Fu, S. P. Yang and J. Liu, "Josephson oscillation and transition to self-trapping for Bose-Einstein condensates in a triple-well trap.", Phys. Rev. A **75**, 033601 (2007).

Thermodynamics of ultracold Fermi gases

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We present recent experimental work on the thermodynamics of strongly interacting Fermi gases. We have developed a general method to probe with high precision the Equation of State (EoS) of locally homogeneous ultracold gases [1,2]. For cold atoms, the density inhomogeneity induced by the trapping potential has long made the connection between the hamiltonian of a homogeneous system and an ultracold gas rather indirect. However careful analysis of *in situ* density profiles can directly provide the EoS of a homogeneous gas. Indeed, assuming the local density approximation, the pressure of a harmonically trapped gas is simply proportional to the integrated *in situ* density profiles[3]. The notorious problem of thermometry of a strongly correlated system is solved by immersing a trace of weakly interacting bosonic ^{7}Li inside the strongly interacting cloud of fermionic ^{6}Li and measuring its temperature after a time-of-flight.

Using this method, we explore the thermodynamics of a two-spin component Fermi gas of ^{6}Li with tunable short-range interactions. First, we focus on the the finite-temperature EoS of the unpolarized unitary gas. We show that the low-temperature properties of the strongly interacting normal phase are well described by Landau's theory of the Fermi liquid and we localize the superfluid transition. We find that none of the existing theories match our experimental data over our full temperature range. Second, we study the EoS in the limit of low-temperatures as a function of interaction strength. In particular, the EoS of the spin-balanced superfluid allows us to make the first quantitative comparison with the theory of low-density bosonic and fermionic superfluids, derived by Lee, Huang and Yang in the late '50. Finally, we address the EoS of the spin-imbalanced gas. We map its phase diagram by measuring the critical spin-polarization for the superfluid/normal quantum phase transition as a function of interaction strength. Moreover we find that for all but the weakest interactions, the partially polarized normal phase behaves as a mixture of two ideal gases: a Fermi gas of majority atoms and a non-interacting gas of dressed quasi-particles, the Fermi polarons.

[1] S. Nascimbene, N. Navon, K. Jiang, F. Chevy, C. Salomon, *Nature* **463**, 1057 (2010).
[2] N. Navon, S. Nascimbene, F. Chevy, C. Salomon, *Science* **328**, 729 (2010).
[3] T. Ho, Q. Zhou, *Nature Physics* **6**, 131 (2009).

Topological quantum phase transitions of attractive spinless fermions in a honeycomb lattice

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[2]*Institut Non Linéaire de Nice, UMR 6618, UNS, CNRS; 1361, route des Lucioles, 06560 Valbonne, France*
[3]*Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117542, Singapore*
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We investigate a spinless Fermi gas trapped in a honeycomb optical lattice with attractive nearest-neighbor interactions. At zero temperature, mean-field theory predicts three quantum phase transitions, two being topological. At low interactions, the system is semi-metallic. Increasing the interaction further, the semi-metal destabilizes into a fully gapped superfluid. At larger interactions, a topological transition occurs and this superfluid phase becomes gapless, with Dirac-like dispersion relations. Finally, increasing again the interaction, a second topological transition occurs and the gapless superfluid is replaced by a different fully gapped superfluid phase. We analyze these different quantum phases as the temperature and the lattice filling are varied.

Virial relations for ultracold trapped Fermi gases with finite range interactions through the BCS-BEC crossover.

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We study the virial relations for ultracold trapped two component Fermi gases in the case of short finite range interactions. Numerical verifications for such relations are reported through the Bardeen-Cooper-Schrieffer (BCS) Bose-Einstein-condensate (BEC) crossover[1], [2]. As an intermediate step, it is necessary to evaluate the partial derivatives of the many body energy with respect to the inverse of the scattering length and with respect to the interaction range. Once the binding energy of the formed molecules in the BEC side is subtracted, the corresponding energy derivatives are found to have extreme values at the unitary limit. The value of the derivative with respect to the potential range in that limit is large enough to yield measurable differences between the total energy and twice the trapping energy unless the interacting system is described by extremely short potential ranges. The virial results are used to check the quality of the variational wave function involved in the calculations.

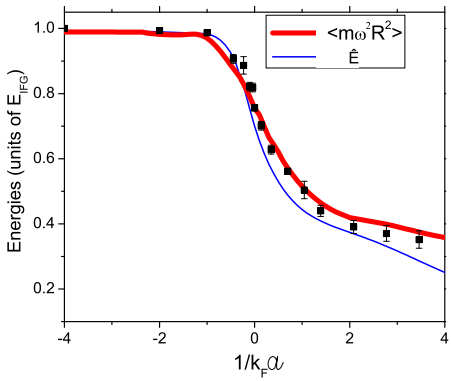

Figure 1: *Energy curves and the mean value of twice the trapping energy* $\langle m\omega^2 R^2 \rangle$ *as predicted by the virial relations. The dots represent the value of the trapping energy obtained directly from the variational wavefunctions.*[1].

[1] L. E. C. Rosales-Zárate and R. Jáuregui. *Virial relations for ultracold trapped Fermi gases with finite range interactions through the Bardeen-Cooper-Schrieffer-Bose-Einstein-condensate crossover.* New Journal of Physics **12**, 043033 (2010)

[2] R. Jáuregui, R. Paredes, L. Rosales-Zárate and G. Toledo Sánchez. *An optimized description of a confined interacting Fermi system*. J. Phys. B: At. Mol. Opt. Phys. **43** 065301 (2010)

Towards Single-Site Imaging of Degenerate Fermi Gas in an Optical Lattice

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Ultracold neutral atoms in an optical lattice is a perfect toy model to simulate and study Hubbard model physics relevant to high temperature superconductivity and other exotic phases of matter. We present the design and construction of a novel apparatus to study these exciting condensed matter systems. The experiment is designed to image degenerate Fermionic Lithium-6 gas in an optical lattice with single site resolution. This high spatial addressibility should allows us to observe the onset of novel quantum phases before any macroscopic properties can be measured.

To achieve single site resolution, we use the 2S to 3P optical transition of the Lithium atom at 323 nm. This short optical wavelength combined with high NA optical system is expected to provide an imaging and projection resolution of about 350 nm, which is smaller than the 532 nm lattice spacing.

High atom detection fidelity can be achieved by using two-photon ionization process using 323 nm and 795 nm photons. The 323 nm light, which is focused down to a single lattice site, transfers the atoms in a single lattice site from the 2S to the 3P state. The 795 nm light, which is illuminated accross a few hundred lattice sites, brings the excited atoms from the 3P state to the ionization continuum. The ion and electron pairs are then detected using single channel electron multiplier. The sequence is then repeated for other lattice sites.

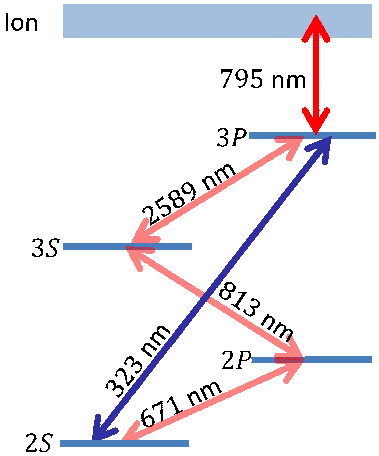

Figure 1: *Relevant energy levels of Lithium atom*

Degenerate quantum gases of strontium

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Most experimental work in the field of ultracold quantum gases is centered on alkali atoms. There is growing interest in two-electron systems such as strontium and ytterbium, since they offer features not found in the alkalis. The lowest triplet-states are metastable and connected to the singlet ground state by narrow intercombination lines, which can be used for optical clocks and precision measurements. All bosonic isotopes have zero nuclear spin, while fermionic isotopes may have large nuclear spins of up to 9/2. This nuclear spin is at the heart of recent proposals to use fermionic alkaline-earth isotopes for quantum computation and simulation [1].

Many of the possible experiments could greatly benefit from the availability of quantum degenerate samples. Strontium has three bosonic (^{84}Sr, ^{86}Sr, and ^{88}Sr) and one fermionic isotope (^{87}Sr). We report on condensation of ^{84}Sr. This isotope has an abundance of only 0.5 %, but its scattering length of $123\,a_0$ is the most favorable among all bosonic isotopes, which makes it very well suited for evaporative cooling. To overcome the low natural abundance, metastable state atoms are accumulated in a magnetic trap. After repumping into the groundstate, they are cooled to μK temperatures on a narrow intercombination line. Loading into a dipole trap and subsequent evaporative cooling are straightforward and very robust, leading to pure condensates of 2.5×10^5 atoms [2].

Many of the afore mentioned proposals rely on the fermionic isotope and require a high degree of control over the internal spin states. As a first step towards realization of the proposed experiments, we cool a spin-polarized sample of ^{87}Sr through interisotope collisons with the bosonic isotope ^{84}Sr. After evaporation, we attain a double-degenerate mixture of 2×10^4 ^{87}Sr atoms at T/T_F of 0.3 and 10^5 ^{84}Sr atoms in a pure BEC [3].

[1] See e.g. the contribution of A. Gorshkov to this conference
[2] S. Stellmer, M. K. Tey, Bo Huang, R. Grimm, and F. Schreck, Phys. Rev. Lett. **103**, 200401 (2009)
[3] M. K. Tey, S. Stellmer, R. Grimm, and F. Schreck, *to be published*

Ordered States and Mott Transition States of Three-Component Repulsive Fermionic Atoms in Optical Lattices

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Motivated by recent experimental results for multicomponent cold fermionic $^{173}\mathrm{Yb}$ atoms [1], we investigate ordered states and Mott transition states of three-component (color) repulsive fermionic atoms in optical lattices. Using the self-energy functional approach and the two-site dynamical mean field theory, we obtain the phase diagram of the three-component Hubbard model at finite temperatures. We clarify that the Mott transition occurs even at incommensurate half filling because of the anisotropy of the interaction. As a result, a paired Mott insulator and a color selective Mott transition (CSMT) state appear. In the former, two atoms with different colors are localized at the same sites and the third color atoms are localized solely at different sites. In the latter, localized two color atoms and the itinerant third color atoms coexist. We show that these exotic Mott phases can be detected by experimental double occupancy observations. Furthermore, we derive the effective model for the CSMT state successfully, which is known as the Falikov-Kimball model for the correlated d- and f- electron systems. The numerical results are discussed using the effective model. We show that the Falikov-Kimball model well describes the CSMT state not only qualitatively but also quantitatively. Therefore, three-component repulsive fermionic atoms in optical lattices work as a quantum simulator for correlated electrons system with coexisting itinerant and localized electrons.

We also investigate the ground state using the dynamical mean field theory [2]. We find that, depending on the anisotropy of the interactions, either a color density-wave (DW) state or a color selective antiferromagnetic (CSAF) state appears at half filling. In the color DW state paired atoms with two different colors and atoms with the third color occupy different sites alternately, while in the CSAF state two color atoms occupying the sites alternately and the itinerant third color atoms coexist. At the SU(3) isotropic interaction point, these two ordered states obey a first-order quantum phase transition.

[1] S. Taie, S. Sugawa, R. Yamazaki, and Y. Takahashi, in Talk of International Symposium on Physics of New Quantum Phases in Superclean Materials, Yokohama, March 2010.

[2] S. Miyatake, K. Inaba, and S. Suga, Phys. Rev. A 81, 021603(R) (2010)

Strong Coupling Effects on the single-particle properties in the BCS-BEC Crossover Regime of Superfluid Fermi Gases

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[2]*Tokyo University of Science, Tokyo, Japan*
[3]*CREST(JST), Saitama, Japan*

We investigate single-particle excitations in the BCS-BEC crossover regime of a superfluid Fermi gas. We include strong pairing fluctations within a T-matrix theory[1], and self-consistently determine the order parameter, as well as Fermi chemical potential, in the superfluid phase below the superfluid transition temperature $T_{\rm c}$. The superfluid density of states (SDOS), as well as the spectral weight (SW), are then calculated from the analytic continued single-particle thermal Green's function over the entire BCS-BEC crossover region.

In the region near the weak-coupling BCS regime, we find that the pseudogap in SDOS (which already appears above $T_{\rm c}$ due to strong pairing fluctuations[2]) smoothly changes into the superfluid gap, as one decreases the temperature below $T_{\rm c}$. In contrast, when the pairing interaction becomes strong in the crossover region, competition between the pseudogap by pairing fluctuations and the BCS gap associated with the superfluid order parameter occurs. Namely, one can see the deformation of pseudogap and the coexistence of these two gap structures in SDOS and SW in the intermediate temperature region, as shown in Fig.1. Our results would be useful for the study of strong pairing fluctuations in the BCS-BEC crossover regime of superfluid Fermi gases.

This work was supported by Global COE Program "High-Level Global Cooperation for Leading-Edge Platform on Access Spaces (C12)," as well as the Japan Society for the Promotion of Science.

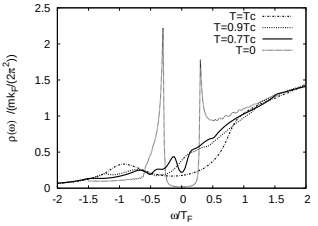

Figure 1: *Temperature dependence of SDOS $\rho(\omega)$ in the unitarity limit. m, $k_{\rm F}$ and $T_{\rm F}$ are the atomic mass, Fermi momentum and Fermi temperature, respectively.*

[1]P. Noziéres, and S. Schmitt-Rink , J. Low. Temp. Phys. **59**, 195(1985), P. Pieri, L. Pisani, and G. C. Strinati, Phys. Rev. B **70**, 094508(2004).

[2]S. Tsuchiya, R. Watanabe, and Y. Ohashi, Phys. Rev. A **80**, 033613(2009).

Benchmark Calculations of Polarizabilities and Long-Range Dispersion Coefficients for Atoms and Ions

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The polarizability of an atom is one of its fundamental properties. They appear in many applications, such as the Stark shift in atomic frequency standards, Stark shifts in spectroscopic measurements of nuclear properties, the magic wavelength for atoms loaded in an optical lattice, and the van der Waals dispersion coefficients between atoms[1,2].

We report our recent work[3,4] on the calculations of static and dynamic dipole polarizabilities for Li and Be^+ in the $2\,^2S$ and $2\,^2P$ states, as well as the dispersion coefficients for Li and Be^+ interacting with rare-gases. Variational calculations in Hylleraas bases, including the finite mass effect, have been performed to determine the low-lying structure and pseudo-spectrum for Li and Be^+. The resulting static and dynamic polarizabilities can be used as benchmarks after the inclusion of relativistic corrections. The final values of the Li and Be^+, 164.11 ± 0.03 a.u. and 24.489 ± 0.004 a.u. can serve as benchmarks for other polarizability applications.

[1]L.-Y. Tang, Z.-C. Yan, T.-Y. Shi, and J. F. Babb, "Nonrelativistic ab initio calculations for $2\,^2S$, $2\,^2P$, and $3\,^2D$ lithium isotopes: Applications to polarizabilities and dispersion interactions", Phys. Rev. A **79**, 062712 (2009).

[2]L.-Y. Tang, J-Y Zhang, Z.-C. Yan, T.-Y. Shi, J. F. Babb, and J. Mitroy, "Calculations of polarizabilities and hyperpolarizabilities for the Be^+ ion", Phys. Rev. A **80**, 042511 (2009).

[3]L.-Y. Tang, Z.-C. Yan, T.-Y. Shi, and J. Mitroy, "Dynamic dipole polarizabilities of the Li atom and Be^+ ion", Phys. Rev. A **81**, 042521 (2010).

[4]L.-Y. Tang, Z.-C. Yan, T.-Y. Shi, J.-Y. Zhang, and J. Mitroy, "Long-range dispersion coefficients for Li, Li^+ and Be^+ interacting with the rare gases", submitted to J. Chem. Phys.

Calculations of Polarizabilities and Hyperpolarizabilities for H_2^+, HD^+, and D_2^+ ions

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Polarizabilities and hyperpolarizabilities of molecules are important in understanding nonlinear optical phenomena, such as light scattering from gases and Kerr effect. Fully correlated basis sets in Hylleraas coordinates, which are capable of including rotational and vibrational degrees of freedom, have been applied to H_2^+ and its isotopolgues. No Born-Oppenheimer approximation (BO) has been assumed. At this conference, we will report our recent work[1] on the calculations of polarizabilities and hyperpolarizabilities of H_2^+, HD^+, and D_2^+ in their ground and excited states using variationally constructed wave functions in Hylleraas basis sets. Dynamic polarizabilities and Stark shifts will also be presented.

[1]L.-Y. Tang, Z.-C. Yan, T.-Y. Shi, and J. F. Babb, "Calculations of the polarizabilities and hyperpolarizabilities for H_2^+, HD^+, and D_2^+", (in preparation).

Variational Calculations for Low-Lying States of Li and Be^+ Using Hylleraas Bases

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In recent years, significant advances have been made in determining nuclear charge radii of lithium and beryllium isotopes[1],[2], including the most interesting halo nuclei of ^{11}Li and ^{11}Be. The underlying principle of the method is to combine high-precision experimental measurements with high-precision atomic structure calculations, including relativistic and QED effects. In this poster, we will report our improved calculations of nonrelativistic energies for some low-lying states of Li and Be^+. By parallelizing our codes in MPI, we can extend the size of basis set up to 27,720 terms in Hylleraas coordinates. As an example, in FORTRAN quadruple precision, the nonrelativistic ground state energy of Li has been calculated to –7.487 060 323 910 099 a.u. without extrapolation, which represents the most accurate (i.e. lowest) variational upper bound to date. The details of our calculations will be presented in the conference.

[1]Z.-C. Yan, W. Nortershauser, and G. W. F. Drake, Phys. Rev. Lett. 100, 243002 (2008) .
[2]M. Puchalski and K. Pachucki, Phys. Rev. A 78, 052511 (2008)

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Coherent correlation in bound 2-fermion interaction: a model for the Higgs boson?

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A bound, spinor coupling model expressed as matter-waves introduces a coherent analytical model of electron-pair correlation. Quantum Spin Coherence (QSC) arising from this model of e-pair coupling presents a computationally scalable, Virial-theorem-compliant, electron correlation strategy in quantum chemistry. Superficial e-pair-coupling models of coherent correlation modes generates a spectrum of spin-harmonic beats: an extended spin-harmonic manifold reflecting the resonant harmonics of spin-coupling within an e-pair is predicted to exist within the ground electronic state of He. Two examples of empirical evidence for such a manifold are advanced. Novel derived force-fields between peer e-pairs, including a transverse, quadrupolar pulsating magnetic field, intrinsic to the symmetry-breaking of coherent e-pair correlation in an axially symmetric field $|L,S\rangle$ representation but operating transverse to each axially aligned e-pair, are predicted to complement a coherent version of the dispersion interaction. A novel attractive form of diamagnetism, peer-resonant coherent dynamic diamagnetism, emerges to generate mass.

An integrated, multi-channel, atom-light interface

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We have constructed a next-generation atom chip using integrated optical waveguide structures. There are 12 buried, single-mode optical waveguides in doped silica, connectorised using V-groove-mounted optical fibres. Light in the waveguides crosses a trench where it can interface with laser-cooled atomic samples (Fig. 1). The chip is integrated into a current-carrying sub-chip for magnetic trapping.

Launching cold atoms into the trench, we have used the absorption of light to demonstrate the presence of, on average, less than 1 atom crossing the mode of a waveguide[1]. One atom causes 2% absorption. We have also successfully used fluorescence detection. Conversely, we have used the atoms to probe the intensity and polarisation of the light.

We have also magnetically trapped and evaporatively cooled large numbers of atoms, working towards placing a trapped atom cloud in the interface. Using weakly-destructive, photon-shot-noise-limited detection, the chip will be capable of local density measurements of BECs to better than atomic shot noise, in real time.

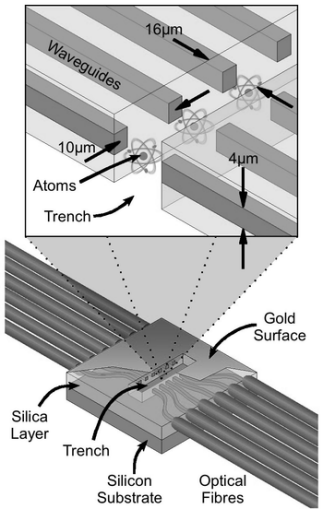

Figure 1: *The optical waveguide chip used to interface light with an atomic cloud. The optical chip sits on a current-carrying structure for magnetic trapping and evaporative cooling.*

[1]M. Kohnen *et al.*, "An integrated atom-photon junction", arXiv:0912.4460v1

A Nanoscale Quantum Interface for Single Atoms

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We propose and analyze a scheme [1] to interface individual neutral atoms with nanoscale solid-state systems. The interface is enabled by optically trapping the atom via the strong near-field generated by a sharp metallic nanotip. We show that under realistic conditions, a neutral atom can be trapped with position uncertainties of just a few nanometers, and within tens of nanometers of other surfaces. Simultaneously, the guided surface plasmon modes of the nanotip allow the atom to be optically manipulated, or for fluorescence photons to be collected, with very high efficiency. Finally, we analyze the surface forces, heating and decoherence rates acting on the trapped atom. In this presentation, we discuss the general properties of these systems, schemes for loading and cooling atoms in very small traps, and current experimental progress toward loading nanowire traps from a Rb MOT.

[1] D.E. Chang *et al*, Phys. Rev. Lett. 103, 123004 (2009)

Quantum signatures of the dynamics of a vibrational mode of a SiN membrane within an optical cavity

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The search for experimental demonstrations of the quantum behavior of macroscopic mechanical resonators is a fast growing field of investigation and recent results have shown the generation of quantum states of resonators with a mass at the nanogram scale[1]. Here we consider the optical manipulation of a mechanical resonator by means of a high-finesse optical cavity. We focus in particular onto the optomechanical system formed by the vibrational modes of a SiN membrane with high mechanical quality factor, driven by the radiation pressure of the stationary modes of a high-finesse cavity[2]. We have studied both theoretically and experimentally such a system. We show that ground state cooling and robust optomechanical entanglement between vibrational modes and both intracavity and output cavity modes is achievable at liquid He temperature. We also provide preliminary experimental results showing how signatures of the quantum behaviour of the motion of a mesoscopic mechanical oscillator could be detected.

[1] A. D. O' Connell *et al.*, Nature, **464**, 697 (2010)
[2] J. D. Thompson *et al.*, Nature **452**, 72 (2008)

Cooling atoms, particles and polarisable objects using dissipative dipole forces

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Optical cooling methods are generally applicable to a very restricted range of species. As a means of overcoming this problem, we explore the effect of the retarded interaction of any polarisable particle (an atom, a molecule or even a micromirror) with itself, similarly to cavity-mediated cooling[1]. We use the transfer matrix method[2], extended to allow us to handle moving scatterers, to explore the most general configuration of a mobile particle interacting with any 1D combination of fixed optical elements. Remarkably, this model allows a solution in closed form for the force acting on the particle, without any *a priori* restriction on the nature of the particle[3].

Mirror-mediated cooling[4] is a powerful extension of optomechanical schemes that can be used to cool an atom using a single plane mirror, but requires a large separation between the atom and the mirror in order to be effective. If the mirror is replaced with a cavity, *outside* of which the atom sits, we show that the cavity acts to 'fold', or multiply, the optical path length, and therefore enhance the friction force acting on the atom, by several orders of magnitude. Crucially, this mechanism can also be applied to the cooling of micromirrors on cantilevers, Figure 1, whereby the efficiency of the optomechanical cooling schemes currently in use can be increased by $\sim 10^4$ simply by adding a second fixed mirror—a significant advance on the current state of the art.

The use of optical resonances on templated surfaces[5], rather than resonances in a cavity, will potentially allow the creation of integrated 2D arrays of micromirrors each coupled to a resonant element that requires no tuning, and each cooled using this 'external cavity cooling' mechanism. This opens up the possibility of investigations into the interactions between light and mesoscopic objects at an unprecedented scale.

Figure 1: *Coupling light interacting with a cantilever to a cavity enhances the optomechanical friction force by several orders of magnitude.*

[1]P. Horak, G. Hechenblaikner, K. Gheri, H. Stecher, and H. Ritsch, Phys. Rev. Lett. **79**, 4974 (1997).
[2]A. Xuereb, P. Domokos, J. Asbóth, P. Horak, and T. Freegarde, Phys. Rev. A **79**, 053810 (2009).
[3]A. Xuereb, T. Freegarde, P. Horak, and P. Domokos, arXiv:1002.0463 (submitted).
[4]A. Xuereb, P. Horak, and T. Freegarde, Phys. Rev. A **80**, 013836 (2009).
[5]N. Cooper, H. Ohadi, A. Xuereb, J. Bateman, and T. Freegarde, poster presented at this conference.

A trapped single ion inside a Bose-Einstein condensate

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In recent years, improved control of the motional and internal quantum states of ultracold neutral atoms and ions has opened intriguing possibilities for quantum simulation and quantum computation. Many-body effects have been explored with hundreds of thousands of quantum-degenerate neutral atoms and coherent light-matter interfaces have been built. Systems of single or a few trapped ions have been used to demonstrate universal quantum computing algorithms and to detect variations of fundamental constants in precision atomic clocks. Now in our experiment we investigate how the two systems can be advantageously combined. We immerse a single trapped Yb+ ion in a Bose-Einstein condensate of Rb atoms[1]. The hybrid setup consists of a linear RF-Paul trap which is overlapped with a magnetic trap and an optical dipole trap for the neutral atoms.

A first synergetic effect is the sympathetic cooling of the trapped ions to very low temperatures through collisions with the ultracold neutral gas and thus without applying laser light to the ions. We observe the dynamics of this effect by measuring the mean ion energy after having an initially hot ion immersed into the condensate for various interaction times, while at the same time monitoring the effects of the collisions on the condensate. The observed ion cooling effect calls for further research into the possibility of using such hybrid systems for the continuous cooling of quantum computers.

To this end a good understanding of the fundamental interaction processes between the ion and the neutrals is essential. We investigate the energy dependant elastic scattering properties by measuring neutral atom losses and temperature increase from an ultracold thermal cloud of Rb. By comparing this with a Monte-Carlo simulation we gain a deeper understanding of how the different parameters affect the collisional effects. Additionally, we observe charge exchange reactions at the single particle level and measure the energy-independent reaction rate constants. The reaction products are identified by in-trap mass spectrometry, revealing the branching ratio between radiative and non-radiative charge exchange processes[2].

Another range of possible applications arises from the high precision with which the ion can be positioned inside the quantum degenerate gas. We demonstrate local probing of the atomic density distribution using a single ion. Combining this with the excellent internal state control we anticipate that this could lead to fundamental studies of the decoherence of a single, locally controlled impurity particle coupled to a quantum environment.

[1] C. Zipkes, S. Palzer, C. Sias, and M. Köhl, Nature 464, 388 (2010).
[2] C. Zipkes, S. Palzer, L. Ratschbacher, C. Sias, and M. Köhl, arXiv:1005.3846

Strong-Field Ionization of Laser-Irradiated Diatomics: The Signatures of Orientation and Inner Shell Effects

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We report the results of our theoretical study of orientation-dependent total ionization rates in strong-field multiphoton above-threshold ionization (ATI) of laser-irradiated homonuclear diatomics (N_2, O_2 and F_2), which are arbitrarily oriented with respect to incident laser field polarization. The problem is studied under conditions of experiment[1] within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA)[2]. In addition, the applied approach essentially exploits the *density-functional-theory* (DFT) method for numerical composition of initial (laser-free) molecular states using the GAUSSIAN-03 code[3]. Besides the ionization from the *highest-occupied molecular orbital* (HOMO, normally predominantly contributing), the contribution from inner valence shells (of higher ionization potential, but different orbital and bonding symmetry) is taken into consideration as well.

The calculated total molecular ionization rates corresponding to either of diatomics under consideration are found to be primarily determined by ionization from respective HOMO and very sensitive to both the respective orbital and bonding symmetry and angle Θ of spatial orientation of molecular internuclear axis relative to incident laser field polarization **e**. Contrary to respective earlier results of other alternative VG-based strong-field approaches, our present findings suggest the correct orientation dependence of calculated total molecular ionization rates that is also fairly well consistent with relevant experiment[1]. In particular, for parallel orientation ($\Theta = 0$), the ionization rate of N_2 is predominantly contributed by photoelectron emission from the *bonding* $3\sigma_g$ HOMO (of *even* orbital symmetry), which is most likely ionized along the internuclear axis, but demonstrates quite a minor ionization for perpendicular directions. Whereas, for perpendicular orientation ($\Theta = \pi/2$), the N_2 ionization can dominate by photoelectron emission from the inner $1\pi_u$ *bonding* valence shell (of higher ionization potential and *even* orbital symmetry), which is primarily ionized along the directions perpendicular to the internuclear axis, but highly suppressed for parallel directions. As a summary result, the calculated total ionization rate of N_2 molecule is found to be about 2.5 times more likely to ionize if aligned along the incident laser field polarization versus the case of perpendicular orientation.

[1] I. V. Litvinyuk et al., Phys. Rev. Lett. **90**, 233003 (2003).
[2] V. I. Usachenko, P. E. Pyak and V. V. Kim, Phys. Rev. A **79**, 023415 (2009).
[3] M. J. Frisch and J. A. Pople, **Gaussian-03, Revision A.1** (Gaussian, Inc., Pittsburgh PA, 2003).

Oral applications of scanned ultra-short laser pulses

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Many efforts have been made so far to replace mechanical tools in oral applications by various laser systems. The reasons for that are manifold: i) friction causes high temperatures damaging adjacent tissue. ii) smear layers and rough surfaces are produced. iii) size and shape of traditional tools are often unsuitable for geometrically complicated incisions and for minimum invasive treatment. iv) mechanical damage of the remaining tissue occurs. v) online diagnosis for feedback is not available.
Different laser systems in the μs and sub-μs-pulse regime, among them Erbium lasers, have been tested in the hope to overcome the mentioned drawbacks and, to some extent, they represent the current state of the art with respect to commercial and hence practical application. In the present work the applicability of scanned ultra-short pulse lasers (USPLs) for biological hard tissue (enamel, dentine, bone, cartilage) and dental restoration material removal, and even for dental implant cleaning, was tested. It is shown that cavities with features superior to mechanically treated or Erbium laser ablated cavities can be generated if appropriate scan algorithms and optimum laser parameters are matched. Smooth cavity rims, no micro-cracks, melting or carbonisation and precise geometry are the advantages of scanned USLP ablation. For bone treatment better healing conditions are expected as the natural structure remains unaffected by the preparation procedure.
The novelty of this work is represented by a comprehensive compilation of various experimental results intended to assess the performance of USPLs. In this context, various pulse durations in the picosecond and femtosecond regime were applied to biological hard tissue as well as dental restoration materials which is considered to be indispensable for a complete assessment. Parameters like ablation rates describing the efficiency of the ablation process, and ablation thresholds were determined - some of them for the first time - and compared to the corresponding Erbium values. The morphology of the tissue surfaces remaining after laser preparation was investigated and the surface roughness was evaluated. Selective ablation was stressed and the temperature impact induced by USPLs was analyzed.
Research in this field is aimed towards commercial implementation which is under a severe financial constraint. To facilitate this approach, additional features are discussed which are as follows: i) intelligent control: only PRR and scan diameter, i.e. speed and 'tool' size, can be adjusted by the user. ii) autofocus: either lens with fast linear motor or lens with adaptable focal length. iii) operation of laser source without mode-locking (cw or chopped) provides radiation for coagulation or endodontics. iv) frequency doubling of non-mode-locked radiation allows for additional indications like e.g. bleaching, biostimulation or decontamination. v) Integration of a laser diode into handpiece or coupling e.g. with pigtail-diode, changeable fiber tips and integrated power supply (generator, etc). This system alone also could be integrated into a dental chair.

Experiments with Two-component Bosons in State-Dependent Optical Lattices

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Mixtures of ultracold bosons in optical lattices allow for the experimental investigation of many interesting models and concepts of condensed matter physics, such as the two-component Bose-Hubbard model with its connection to quantum magnetism, effects of impurities and disorder, and phonon-mediated effects.

Here, we report on our recent work with binary hyperfine-state mixtures of ^{87}Rb in a three-dimensional optical lattice with an individually controllable lattice depth for each state along one axis. This allows for a state-selective superfluid-to-Mott insulator transition, as shown in Fig. 1 (A). We have studied how the superfluid coherence of a 'foreground' component, chosen close to the Mott regime, is affected by the presence of a 'background' component which is varied from a highly superfluid state to a strongly localized Mott state.[1] In both cases, we find a significant reduction of the coherence of the foreground component. We ascribe this to a polaron-like dressing[2] in the first case, and to the formation of a quantum emulsion[3] in the second case.

Moreover, we have observed two-component four-wave mixing with macroscopically populated modes in a collinear geometry.[4] The combination of momentum and internal degrees of freedom, illustrated in Fig. 1 (B), should make this system interesting for quantum atom optics. Further, we show that such four-wave mixing can affect studies of bosonic mixtures loaded into state-dependent optical lattices.

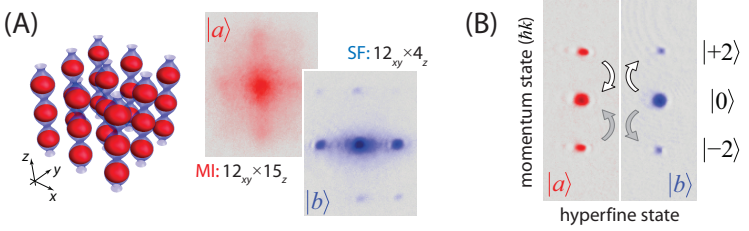

Figure 1: *(A) State-selective SF-MI transition: Component $|a\rangle$ is in the Mott regime, while component $|b\rangle$ stays superfluid. Lattice depths along the respective axes are given in recoil energies. (B) Collinear four-wave mixing with two-component matter waves. Arrows indicate coherent transfer between the modes due to four-wave mixing.*

* *Present address: Institut für Angewandte Physik, Universität Bonn, 53115 Bonn, Germany*

[1] B. Gadway, D. Pertot, R. Reimann, and D. Schneble, arXiv:1002.4015

[2] M. Bruderer, A. Klein, S. R. Clark, and D. Jaksch, Phys. Rev. A **76**, 011605 (2007)

[3] T. Roscilde and J. I. Cirac, Phys. Rev. Lett. **98**, 190402 (2007)

[4] D. Pertot, B. Gadway, and D. Schneble, Phys. Rev. Lett. **104**, 200402 (2010)

Ultracold fermions in optical lattices: Simulating condensed matter systems and beyond

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Ultracold Fermions in optical lattices are an almost ideal model system to study strongly correlated condensed matter physics: They offer a clean and defect-free implementation of the fermionic Hubbard model combined with an unprecedented control over all relevant parameters. I will present important advances made in previous years in our group concerning the preparation and analysis of strongly correlated many-body states in these systems. This enabled the observation of the fermionic Mott insulator [1] in the repulsive Hubbard model and the Pseudo-gap regime[2] for attractive interactions. In addition, we studied the free expansion of fermionic ^{40}K atoms in a homogeneous optical lattice. We observe a crossover from diffusive behavior in the center of the cloud to a ballistic motion of atoms in its outer regions. This crossover manifests itself in a striking change of the cloud's shape. Surprisingly, the system exhibits a strong feedback from the ballistic on the diffusive regions. These measurements demonstrate a previously unobserved transport dynamics, which is independent of the sign of interactions, and give insight into the characteristic timescales of density redistribution[3].

[1]Metallic and Insulating Phases of Repulsively Interacting Fermions in a 3D Optical Lattice, U. Schneider *et.al*, Science **322**, 1520 (2008)

[2]Anomalous Expansion of Attractively Interacting Fermionic Atoms in an Optical Lattice, L. Hackermüller *et.al*, Science **327**, 1621 (2010)

[3]Breakdown of diffusion: From collisional hydrodynamics to a continuous quantum walk in a homogeneous Hubbard model, U. Schneider *et.al*, arXiv:1005.3545 (2010)

Variational study on Mott transition in the S=1 two-dimensional Bose-Hubbard model

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[3]*JST CREST, Japan*
[4]*Department of Physics Tohoku University, Sendai, Japan*

Various phase structures of ultracold atoms in optical lattices have attracted much attention after the observation of the superfluid-Mott insulator (SF-MI) transition with spin-0 bosons. Recently, it is realized that bosons with the spin degree of freedom have trapped in an optical lattice. Up to now, several theoretical works have addressed the SF-MI transition in the spinor bosons trapped in optical lattices. In one-dimensional cases, M. Rizzi *et al.* used DMRG method to accurately determine the phase diagram for spin-1 Bose-Hubbard model (BHM)[1]. However, in higher dimensional cases it only works with mean-field theory[2].

We theoretically study the Mott transition in the S=1 two-dimensional BHM using a variational Monte Carlo technique. It is known that longer range correlation factors such as a multiplon-holon-binding[3] (M-H) or a Jastrow-type[4] projection should be incorporated in the conventional Gutzwiller variational wave function to properly describe the Mott transition in the fermionic Hubbard model and S=0 BHM. Thus we study the Mott transition in the S=1 BHM based on the Gutzwiller wave function with a M-H factor. Fig.1 shows the total energy per site as a function of U_0/t for U_2=0.3U_0. Here, t is the hopping term, U_0 is the onsite spin-independent interaction and U_2 is the onsite spin-dependent interaction in the S=1 BHM. We found that the M-H factor improve estimation of the total energy. We will discuss the detailed structure of the phase diagram and the spin correlations in the S=1 BHM.

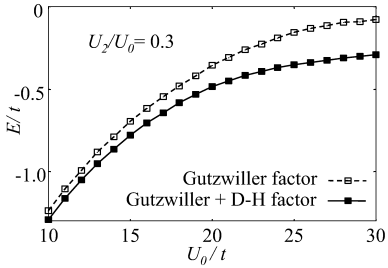

Figure 1: *Total enegy per site as a funcion of U_0/t. The number of square lattice sites is 6×6 sites and the particle density is commensurate (n=1.0).*

[1]M. Rizzi, D. Rossini, G. De Chiara, S. Montangero, and R. Fazio, Phys. Rev. Lett. **95**, 240404 (2005).
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Towards Ultracold Atoms in Exotic Optical Traps

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We present our ongoing construction of two single-chamber setups for the production of a ^{87}Rb Bose-Einstein Condensate and a Magneto-Optical Trap for ^{6}Li and ^{87}Rb atoms loaded from alkali-metal dispensers. We also discuss investigations of pulsed techniques[1,2] in each apparatus to achieve large atom numbers at low background pressure for an efficient evaporative cooling.

In the field of ultracold atoms, the full control over the atomic interactions of ultracold bosons or fermions and the high tunability of optical lattices provide an excellent platform for quantum simulations, leading to results such as the observation of the superfluid-Mott insulator transition. The standard technique to create these lattices is by using standing waves of light. However, in our experiment we plan to use a Spatial Light Modulator (SLM) as an alternative to create more diverse and flexible trapping potentials. The first demonstration of this was made in Oxford where a ^{87}Rb BEC containing 10^5 atoms was split into two or three parts using an optical trap generated with a SLM[3].

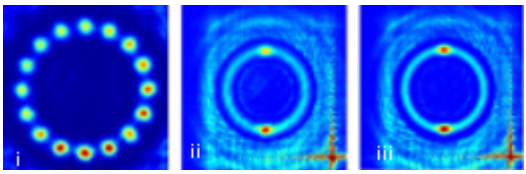

Figure 1: *Discrete and continuous light distributions generated with a SLM: (i) an infinite length 1D lattice to study quantum tunneling of atoms between sites and (ii) a continuous ring with two peaks that can be rotated and where these two regions could act to 'stir' the atoms and induce an atomic superflow through the trap. Both patterns were generated by IFTAs. (iii) The pattern from (ii) can be improved by using our new algorithm, which uses a feedback loop to remove any aberrations.*

We show initial investigations of the possibilities for trapping ultracold atoms in non-trivial geometries by using holographically-generated optical potentials. It is possible to generate discrete or continuous patterns and even dynamic geometries, going beyond those presently achievable using standard techniques. Calculating the phase pattern to generate high-quality exotic light patterns is non-trivial so this requires sophisticated Iterative Fourier Transform Algorithms (IFTAs)[4]. By improving existing algorithms, we have produced smoother ligth patterns, imaged using a CCD camera, as shown in Figure 1, and we also suggest some applications with ultracold atomic systems.

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Diatomic Molecules in Optical Dipole Traps

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An atomic- or molecular system subject to the electric field $\vec{\mathcal{E}}$ of a laser beam experiences an induced dipole moment $\vec{P}$ given by the relation $\vec{P} = \alpha\vec{\mathcal{E}}$, where α denotes the complex polarizability. Associated with the induced dipole moment $\vec{P}$ in the driving field $\vec{\mathcal{E}}$ there is an interaction potential $U_{\rm dip}$ given by $U_{\rm dip} = -\frac{1}{2}\langle\vec{P}\cdot\vec{\mathcal{E}}\rangle = -\frac{1}{2\epsilon_0 c}\mathrm{Re}(\alpha)I$, where I is the field intensity, $I = 2\epsilon_0 c|\vec{\mathcal{E}}|^2$. Hence, the interaction with the laser field is governed by the complex polarizability, which for a state $|\Psi_n\rangle$ is defined by the following rather complex expression:

$$\alpha_n(\omega) = 2\sum_{k(k\neq n)} \frac{\left(E_k - E_n - \frac{i\hbar}{2}\Gamma_k\right)|\langle\Psi_k|P_\mu|\Psi_n\rangle|^2}{\left(E_k - E_n - \frac{i\hbar}{2}\Gamma_k\right)^2 - \hbar^2\omega^2}, \tag{1}$$

where ω denotes the laser frequency, and P_μ indicates a spherical component of the dipole moment in a space-fixed coordinate system. The quantity Γ_k is related to the lifetime (spontaneous emission) of the (exited) state $|\Psi_k\rangle$, and defined by:

$$\Gamma_k = \frac{1}{3\pi\epsilon_0 c^3}\sum_{l(l\neq k)} (E_k - E_l)^3|\langle\Psi_k|P_\mu|\Psi_l\rangle|^2, \qquad (E_k > E_l). \tag{2}$$

Finally, the imaginary part of the polarizability gives the scattering rate $\Gamma_{\rm sc}$ (number of photons emitted pr. s): $\Gamma_{\rm sc} = \frac{1}{\hbar\epsilon_0 c}\mathrm{Im}(\alpha)I$.

The subject of atoms in optical traps is well investigated [1]. Alkali atoms like Na and Rb represent two-level systems, i.e. a ^2S ground state interacting with the first excited ^2P state.

For diatomic molecules there are extra challenges as well as extra opportunities. First there is the problem of working out the transition moment $\langle\Psi_k|P_\mu|\Psi_n\rangle$ in a molecule-fixed coordinate system, taking into account the rotational- and vibrational motions in addition to its electronic state. For homonuclear molecules there is also the complication of nuclear spin weight factors, and a rather complicated hyperfine structure. Contrary to atoms, molecules are multi-level systems, which means that for large detunings of the laser frequency a series of excited molecular states will contribute to the trapping potential, as well as to the rate of spontaneous emission and the scattering rate.

The poster will present computed trapping potentials and scattering rates for the OH-molecule. This molecule has a rich multitude of states related to hyperfine interaction, Λ-doubling, rotation and electronic spin effects. Thus, it offers a variety of trapping potentials, depending on the preparation (pumping) of its initial state, the laser detuning, and the polarization of the laser light. Results will also be presented for the simpler $\mathrm{Na_2}$ molecule, where, however, nuclear spin weight factors play an important role.

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New quantum phases in triangular and hexagonal optical lattices

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The physics of ultracold quantum gases in optical lattices has developed to a fascinating field with many connections to different areas like condensed matter physics, quantum computing or ultracold chemistry. We have realized a novel type of magnetic, optical lattice with hexagonal symmetry, where atoms of different spin quantum number feel different potentials. This leads to a forced magnetic ordering and state-dependent Mott-insulator transition points or more generally to new options to study magnetism in optical lattices. In particular, we show that in case of a bosonic spin-mixture, interaction induced blocking of tunneling occurs. Using a specially adapted type of microwave spectroscopy, we have studied the localization properties of the system for different parameter regimes. A forced antiferromagnetic ordering and the generation of a forced supersolid have been observed[1].

Minor changes in the experimental setup allow for the creation of a spin-independent triangular optical lattice[2]. By extending the system to a driven triangular lattice[3], we have been able to observe first signs of a Néel ordered state and a frustrated magnetic system and we present the recent data in that direction.

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Forming Bose-Einstein gap solitons on the background

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By analytically solving the one-dimensional (1D) Gross-Pitaevskii equation (GPE), we found that Bose-Einstein gap solitons are formed on top of the background atoms which pile up from the bottom of the optical potential. The calculated atom numbers of both background and gap soliton are quantitatively consistent with the experimental observation of Eiermann et al.[1]

The analytical nonlinear wavefunction for the gap soliton with anomalous dispersion realized at the Brillouin zone boundary, shown in Fig. 1, is $\Phi(X) = Asech(BX)cos(\frac{\pi X}{2})$ with $A = \sqrt{|\frac{2\delta}{\sigma}|}$, $B = \sqrt{2\,|m_a^*|\,\delta}$, effective mass m_a^*, interatomic interaction σ, and detuning chemical potential δ.

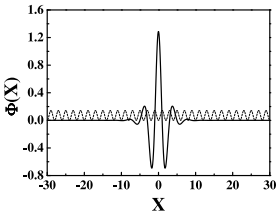

Figure 1: *Spatial distribution of the gap soliton with the optical lattice in dashed curves.*

The atom number of the soliton from this wavefunction (open circles) is in excellent agreement with that of experimental observation (solid circles) in Fig. 2.

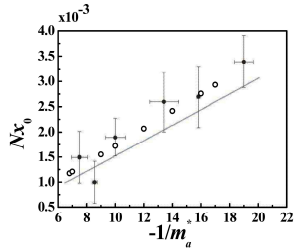

Figure 2: *Product of soliton atom number N and width x_0. The solid (open) circles are from the experimental data* [1] *(our analytical result).*

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One Dimensional controllable optical lattice with intra-cavity EO crystal tuned ECDL

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A controllable optical lattice provides a tool to study many effects in condensed matter physics, such as Zener tunneling, Bloch oscillation, et al. Here, we develop a stable and controllable technique to produce an optical lattice. One dimensional (1D) optical lattice is formed with a focused red-detuned laser and its retro-reflected beam through a lens and a mirror, as shown in figure 1. When the lattice laser frequency is tuned, the standing wave nodes and peaks also moved.

A method of fast laser frequency tuning of external cavity diode laser (ECDL) by intra-cavity electro-optical crystal[1] is applied as the lattice laser. The tuning rate can reach 10 MHz/μs, which has better than 1 order of traditional PZT-tuned ECDL or Ti:sapphire laser. Choosing the experimental parameters as which in figure 1, the maximum speed of 1D optical lattice can reach 3.8 times of recoil velocity v_r.

In this experiment, we use a ECDL laser with about -100 GHz detuning and about 2 mW power to produce an 1D optical lattice with about 300 E_R lattice depth. And the 1D moving optical lattice was pulsed loaded on an almost pure BEC[2] within 100μs duration. We detect the momentum evolution under the moving lattice with speed of about 1 v_r and 3 v_r by time-of-flight measurement. The experiment result can be fitted by theoretical calculation.

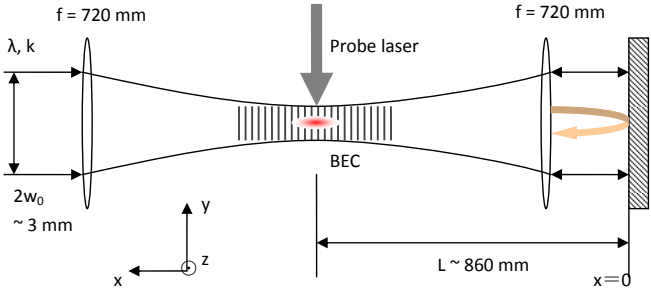

Figure 1: *The setup of 1D optical lattice which loaded on a pure BEC.*

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Number Squeezing and Spectroscopic Line Shape of an Array of Ytterbium Condensates in a 1D optical lattice

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A realization of Bose-Einstein condensation in ultracold atomic gases has opened up the possibilities of highly accurate interferometric measurement based on the atomic de Broglie waves. From the knowledge of quantum optics, one can expect that the use of squeezed states will dramatically improve the sensitivity of atom interferometry below the shot-noise limit. Atom-number-squeezed states have been successfully demonstrated using an array of condensates confined in a one-dimensional optical lattice[1]. It has been clarified that many-body effects caused by inter-atomic interactions strongly reduce the number fluctuations of condensed atoms as the optical lattice potential becomes deeper.

We theoretically study the ground state properties of an array of Bose-Einstein condensates trapped in a one-dimensional (1D) optical lattice. We quantitatively compare our calculated results with the recent experimental results by Kyoto University group using ^{174}Yb atoms[2]. The present system is described by the extended version of the 1D Bose-Hubbard model in which both the tunneling matrix element and the onsite atomic interaction depend on the lattice sites due to the interaction broadening of localized Wannier function. An external harmonic confining potential inherent in the experiments is also considered in our model. We employed the highly efficient numerical method based on the Gutzwiller approximation to deal with the large inhomogeneous system in the regime of the experiments. We show that atomic states are highly number squeezed as the depth of lattice potential increases, which is consistent with the experimental results of time-of-flight images. Furthermore, we calculate the spectroscopic line shape for Yb condensates in a 1D optical lattice. The obtained inhomogeneous broadening induced by atomic interactions agrees well with the high-resolution spectra observed experimentally by using the ultranarrow $^1S_0 - ^3P_2$ transition.

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Partially coherent electron diffraction of biomolecules using an ultracold plasma electron source

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The molecular structure of biological molecules such as *bacteriorhodopsin* can be determined by electron diffraction, but general application of the technique has been limited by the brightness of conventional electron sources. Brightness is proportional to current and inversely proportional to temperature. Recent advances in atomic physics have made the prospect of high brightness electron beams from cold atomic clouds a promising alternative to conventional high temperature (10^4 K) bright electron sources such as the rf photogun.[1,2]

Cold atoms in a magneto-optic trap (MOT) can be photoionised with a laser tuned just above threshold, releasing electron bunches with temperatures as low as 10 K. The number of electrons that can be extracted from a MOT is relatively small compared to that from rf photoguns, but the dramatic reduction in temperature should enable greater overall brightness. Although the source is extended compared to high coherence field emission tips, the transverse coherence length of the electron bunches is sufficient for diffractive imaging of molecules such as *bacteriorhodopsin*. We are evaluating the imaging potential of ultracold plasma sources, in particular the effects of transverse coherence and source size, by adapting partially coherent diffraction techniques developed for x-ray diffraction.[3]

For thin 2D samples such as *bacteriorhodopsin* we assume the far field intensity recorded on our detector is related simply to the initial molecular potential $V(\vec{r})$ and the incident electron wave by $I(\vec{u}) = |\hat{F}[V(\vec{r})]\hat{F}[\Psi_m(\vec{r})]|^2$, where $\hat{F}$ is the Fourier transform and $\Psi_m(\vec{r})$ is a linear decomposition of the wave into weighted propagation modes. We model the electron density $\rho(\vec{r})$ and hence $V(\vec{r})$ by a linear combination of Gaussian functions to approximate a Slater-type atomic orbital basis set.[4]

The simulated results incorporate our range of experimental parameters such as source size, geometry, brightness and electron energy. We first model electron biprism and double slit coherence measurement schemes to evaluate the feasibility of experimental determination of the source charactersitics. We also evaluate the potential of our electron source to accurately reconstruct the molecular structure of the well-characterised *bacteriorhodopsin* 2D crystal.

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Beam diagnostics for Helium beam microscopy

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Focusing of neutral atomic beams in two dimensions using intense pulsed lasers can provide a suitable probe for application in neutral atom microscopy. The spatial and temporal profile of this atom probe (beam focus) are highly dependent on the velocity and density characteristics of the unfocused beam.

We describe an approach that allows for absolute density measurement of rotationally-symmetric atomic beams via multiphoton ionization (MPI) [1]. This single-projection tomographic technique requires only knowledge of the spatial intensity profile and ionization characteristics of the focused laser beam that probes the pulsed atomic jet. We have shown that multiphoton ionization of Xenon and Helium beams (see Figure 1) allows tomographic reconstruction of 2D density profiles, which can be compared to the theoretical predictions of the sudden freeze model. An analytic solution to the Abel transform, derived for Gaussian projected density profiles, greatly simplifies the reconstruction of the absolute radial density. MPI is sufficiently general that this technique can be readily applied to atomic or molecular beams with a broad range of chemistries. Additionally, MPI is a useful technique for helium detection in atom microscopy experiments producing effective ionization volumes of the order of 10^{-15} m^3 with nanosecond temporal resolution.

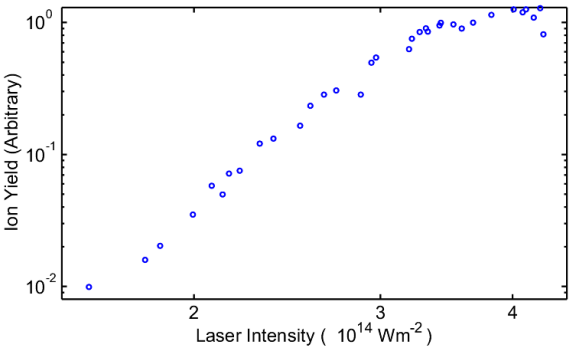

Figure 1: *The ion yield curve for Helium excited by a 355nm frequency tripled Nd:YAG laser beam indicates that ionization occurs as a 7 photon process.*

Excitation of metastable states in Xenon and Helium allowed time of flight experiments to be used to characterise the temperature and velocity of the molecular beams. A Helium jet with a velocity of 1780 ms^{-1} and a speed ratio $S = 60$ (T=0.2K) can be produced which is sufficiently cold to allow optical focusing to a probe as small as 100nm depending on the laser's pointing stability.

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Electron Evaporation from an Ultracold Plasma

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Electrons in an expanding ultracold plasma are expected to be in quasi-equilibrium, since the collision times are short compared to the plasma lifetime, yet we observe electrons evaporating out as the ion density decreases during expansion. We observe that a small electric field that shifts the electron cloud with respect to the ions increases the evaporation rate. By treating the electrons as a zero-temperature fluid, we have calculated their spatial distribution given a fixed Gaussian ion density and applied field. The zero-temperature approximation gives the maximum number of electrons that can be held in the plasma in the absence of evaporation. Performing this calculation at all times allows us to predict the flux of cold electrons from the plasma, which is in good agreement with our measured electron signal. In addition, short electric field pulses can dump a fraction of plasma electrons without affecting the ion expansion. Evaporation ceases for several microseconds before quickly refilling to match the shape of the unperturbed signal. We discuss the possibility of using this and other measurements to probe the thermal distribution of electrons.