Using cold molecules to detect molecular parity violation

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Heavy diatomic molecules are of great interest for the study of fundamental interactions and symmetries. They offer a unique sensitivity, for example, to probe the size of the dipole moment of the electron[1], or to detect parity violation[2]. The recent advances in the manipulation of molecules have been tremendous[3]. We combine the latest techniques to decelerate and cool molecules to probe for signs of molecular parity violation. Parity violation has so far never been observed in molecules.

Parity-violating effects, originating from the weak interaction, scale strongly with the mass of the molecule. Stark-deceleration of heavy molecules is more difficult compared to light molecules such as NH[4] and OH[5]. It is still unforeseeable how to obtain cold trapped chiral molecules, but with recent advances in Stark-deceleration[6] it has become realistic to stop and trap a class of heavy diatomic molecules. Such molecules have been proposed to probe nuclear-spin dependent parity violation[2].

Our candidate molecule is SrF. We are currently working on a supersonic beam of SrF molecules, constructing a Stark-decelerator based on ring electrodes, and exploring the opportunities for molecular lasercooling. A new generation of precision measurements to probe fundamental interactions and symmetries can be done once sufficiently cold molecules are available.

[1] Hudson et al, Phys. Rev. Lett., **89**, 23003, (2002)
[2] DeMille et al, Phys. Rev. Lett., **100**, 23003 (2008)
[3] Carr et al, New J. Phys., **11**, 055049 (2009)
[4] Hoekstra et al, Phys. Rev. A, **76**, 63408 (2007)
[5] Hoekstra et al, Phys. Rev. Lett. **98**, 133001, (2007)
[6] Osterwalder et al, Phys. Rev. A **81**, 051401(R) (2010)

Dynamics of ultracold polar molecules in a microwave field.

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We analyze the temporal evolution of the ultracold molecular population in a microwave field with a circular polarization. Ultracold samples of polar molecules(KRb and $LiCs$) in the ground ro-vibrational state have been obtained in recent experiments[1] and the microwave trap for polar molecules was suggested in [2]. Being electrically polarized enough such molecules mostly interact via strong long-range anisotropic dipole-dipole forces. For $^1\Sigma$ state polar molecules the collisional dynamics in a field is mostly controlled by two ratios ν/B and $x = \mu E/hB$ (ν is the microwave frequency, B is the molecular rotational constant, μ is the dipole moment, and E is the electric field strength). We are mostly interested in the lowest energy strong-field-seeking state of the ground vibrational and rotational $|J = 0, M = 0 >$ state. At such cold temperatures ($1\mu K - 1mK$) the characteristic collision time is considerably larger than the period of oscillation of the molecule in the microwave field and thus molecules are already essentially dressed at quite a low strength of the field (tens of V/cm).That is why even "ground state" molecules may have rather large inelastic cross sections(Fig.1).

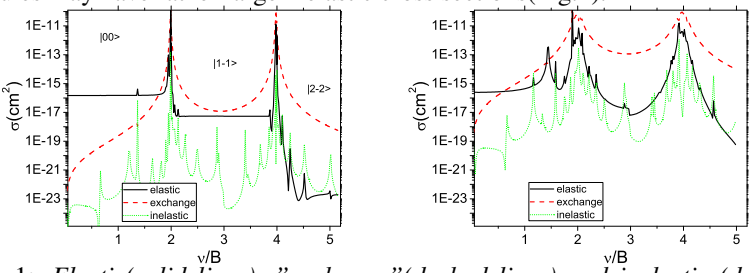

Figure 1: *Elastic(solid lines), "exchange"(dashed lines) and inelastic (dotted lines) cross sections versus the frequency of the microwave electric field at the collision energy* $1\mu K$ *for a)*$x = 0.01$ *and b)*$x = 0.1$ *strengths. This example is for fermionic molecules.*

As we demonstrate such transitions are mostly of exchange nature, namely, this process is mostly ruled by an exchange of states $|0, 0 >$ and $|1, -1 >$ between colliding molecules. But the dipole-dipole interaction can both enhance such an exchange and destroy the natural superpositions of these states in a field[3]; besides, it causes the growth of the inelastic cross section with increasing the field strength(Fig.1b). Taking into account such inelastic collisions rates we solve and analyze the master equation for dressed molecules in dependence on a microwave field parameters and for both bosonic and fermionic species.

[1]K.K.Ni et.al., Science **322**, 231 (2008); J.Deiglmayr et.al., Phys.Rev.Lett. **101**, 133004 (2008)
[2]D. DeMille, D. R. Glenn, and J. Petricka, Euro. Phys.J.D **31**, 375 (2004)
[3]A.V.Avdeenkov, New J.Phys. **11**,055016 (2009)

RF-association spectroscopy of $^{41}K^{87}Rb$ Feshbach molecules : toward the production of ultracold bosonic polar molecules

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Ultracold polar molecules are known as a novel physical system due to their anisotropic and long-range dipole-dipole interactions. Recently ultracold fermionic polar molecules were made by JILA's group[1] and their collisional properties including chemical reactions were investigated[2]. Our final goal is making ultracold bosonic polar molecules using ^{41}K and ^{87}Rb atoms and realizing of quantum degenerated polar molecules. So far we successfully produced a degenerate mixture of ^{41}K and ^{87}Rb atoms. We are planning to transfer Feshbach molecules into the absolute ground state using STIRAP.

So we performed the RF-association experiment similar to the experiment with ^{40}K and ^{87}Rb atoms[3]. Figure 1 shows the measured binding energy of Feshbach molecules which are associated by the RF field whose frequency is well resolved from the atomic transition of the $|F = 1, m_F = 0 >$ to $|F = 1, m_F = 1 >$ transition of ^{41}K atom. Measured binding energy is consistent with the previous measurment obtained by modulating the Feshbach field[4].

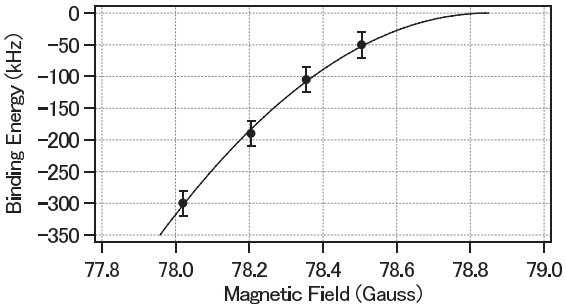

Figure 1: *Measured binding energy of $^{41}K^{87}Rb$ Feshbach molecules.*

[1]K.-K. Ni et al., Science 322, 231(2008)
[2]S. Ospelkaus et al., Science 327, 853 (2010)
[3]C. Ospelkaus et al., Phys. Rev. Lett. 100, 120402 (2006)
[4]C. Weber et al., Phys. Rev. A 78, 061601(R) (2008)

Relativistic calculations of ground and excited states of LiYb molecule for ultracold photo association spectroscopy studies

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Photo association experiments on ultracold polar molecules have opened up many exciting possibilities.[1] An experiment on LiYb system is being planned and work towards cooling and trapping are underway.[2] To assist these experiments, we perform a series of quantum-chemical calculations for the ground and some of the low-lying excited states by the spin-orbit multi-state complete active space second-order perturbation theory (SO-MS-CASPT2).

In this study we include all the electronic states which dissociate to Li($^2S_{1/2}$) + Yb ($^1S_0$), Li ($^2P_{1/2,3/2}$) + Yb ($^1S_0$), Li ($^2S_{1/2}$) + Yb ($^3P_{0,1,2}$), and Li ($^2S_{1/2}$) + Yb ($^1P_1$) as they are the candidate states of S-P transition of photo association experiments in LiYb. The corresponding spectroscopic constants at the spin-free and spin-orbit level will be presented. Atomic experimental excitation energies are compared with the excitation energies of the super-molecule at 100 a.u. bond distance, as a check on the asymptotic limits. Examining the spin-free and spin-orbit potential energy curves, we find the structure to be similar except for the states dissociating to Yb(^3P) asymptotic limits, which shows more complicated levels due to spin-orbit effect. To support the photo association experiments on LiYb system, we also present the permanent and transition dipole moments (TDMs) based on the present potential energy curves both at spin-free and spin-orbit levels of calculation. Spin-orbit effect leads to more possible non-zero transitions in the TDM calculations. The accuracy of our TDM calculations are checked by comparing results at dissociated regions (R = 100 a.u.) with available experimental and theoretical atomic data. .

[1] R. V. Krems, B. Friedrich, W. C. Stwalley, Cold Molecules: Theory, Experiment, Applications, CRC Press, Boca Raton, FL (2009)

[2] M. Okano, H. Hara, M. Muramatsu, K. Doi, S. Uetake, Y. Takasu and Y. Takahashi, Simultaneous magneto-optical trapping of lithium and ytterbium atoms towards production of ultracold polar molecules, Appl.Phys.B (DOI10.1007/s00340-009-3728-0)

Ultracold gas of ground-state polar KRb molecules in 2D

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We report on our ongoing studies of dipolar interactions in ground-state KRb molecules prepared in the quantum regime. At large dipole moment we see a dramatic increase in the inelastic scattering rate due to attractive head-to-tail interactions between molecules[1]. To suppress this inelastic loss we prepare a gas of polar molecules in a 2D confined geometry provided by a one-dimensional optical lattice. By preventing attractive head-to-tail dipolar collisions the inelastic loss rate is suppressed by more than a factor of 40 at high dipole moments.

[1] K.-K. Ni, S. Ospelkaus, D. Wang, G. Quemener, B. Neyenhuis, M. H. G. de Miranda, J. L. Bohn, J. Ye, D. S. Jin, Dipolar collisions of polar molecules in the quantum regime. Nature **464**, 1324 (2010).

Laser Cooling of Molecules by Zero Velocity Selection and Single Spontaneous Emission

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Translational laser cooling of molecules by repeated spontaneous emissions is considered to be impractical due to the difficulty of maintaining closed pumping cycle with several molecular levels. Spontaneous emissions populate many vibrational and rotational levels and would require many lasers to recycle the pumping process. Vuletic and Chu have proposed using optical cavity for dissipation to circumvent the closed pumping cycle problem. We proposed a scheme that circumvents the many levels in molecules through single spontaneous emission. Here, we present a laser cooling scheme for molecules that is more practical. It is based on repeated cycles of three steps: zero velocity selection, deceleration by STIRAP and irreversible accumulation. Single spontaneous emission is used to circumvent the multi-level energy in molecules. The setup involves a Stark barrel. Numerical simulations with parameters for OH molecules show the applicability of the cooling scheme.

Initially, a hot gas of molecules is prepared predominantly in a reservoir state $|g_i\rangle$. First, a "cooled" ensemble of molecules with narrow momentum width and zero mean is selected by coherent Raman technique and transferred to an excited vibronic level $|g_{vs}\rangle$. Spontaneously decay populates a limited number of ro-vibrational states $|acc\rangle$. In order to accumulate the "cooled" ensemble in $|acc\rangle$, we repeat the zero velocity selection process. Before this can be done, we create finite population around zero momentum in $|g_i\rangle$ using the stimulated Raman adiabatic passage (STIRAP) deceleration. Then, the zero velocity selection and accumulation can be repeated.

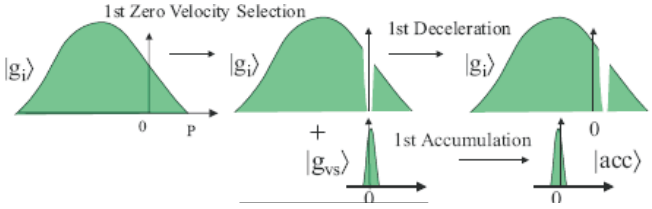

Figure 1: *Momentum distributions in the initial $|g_i\rangle$, velocity selected $|g_{vs}\rangle$ and accumulation $|acc\rangle$ states in each of the three cooling steps.*

Low-Energy Collisions of Ammonia and Rubidium

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Recently, great progress has been made in the production of trapped cold molecular samples via many different techniques. There are many motivations for producing such samples, including the ability to study low-energy collisions in a regime where the interactions are dominated by long-range forces and resonances and, also the ability to control the interacting species by the application of external fields. In our research, we study the interaction between ammonia and rubidium. Recent calculations have shown that that the inelastic cross section for Rb-ND_3 system is well below the Langevin capture limit[1], suggesting the interaction is approximately adiabatic. This adiabaticity may be a result of the projection of the ND_3 onto a space-fixed axis by its interaction with the Rb atom. We investigate this interaction experimentally by separately trapping ammonia and rubidium and then overlaying the two traps to study the interaction between the two species. The cold sample of ammonia is prepared by Stark deceleration of a cold molecular beam of ammonia, which is then loaded into an electro-static trap. The rubidium is loaded from a magneto-optical trap into a purely magnetic trap and then overlaid with the ammonia. We then measure the inelastic cross-section between the rubidium and ammonia. Experiments in this energy regime will lead to better understanding of chemical dynamics and reaction processes.

[1] P.S. Zuchowski and Jeremy Hutson, "Low-energy collisions of NH_3 and ND_3 with ultracold Rb atoms", Phys Rev A 79, 062708 (2009)

Vibrational quantum defect to analyse weakly-bound molecules. Application to Cs_2 to detect coupled states

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To form cold molecules starting from cold atoms, many processes have been demonstrated: for example the photoassociation (PA) or the magneto-association. In the case of the PA use, the scheme which ends to a molecule in the ground state is generally composed by many steps. The simplest scheme uses two steps:(1) the PA of a pair of cold atoms to an excited molecule and (2) a natural or induced decay of the excited molecule to a ground state.

The both steps are optimized when the intermediate state (of the excited molecule) has a wavefunction with two regions of large probability: one at long range distance ideal for PA process- and another one at short range distance - ideal for decay into a vibrational ground state. Such wavefunctions occasionally exist when the state results of the coupling between two molecular curves, in the vicinity of quasi resonant levels.

To detect such intermediate states, a careful analysis of the spectroscopic data is required. In this context, we have proposed and applied the method of the vibrational quantum defect [1] to analyse spectroscopic data of weakly-bound molecules. The method which joins the LeRoy-Bernstein formula and the quantum defect theory is very efficient to detect quasi-resonant coupled states. In a simple model of coupled series, the amplitude of the coupling, the location of the levels and the mixing of the wavefunctions are then determined.

We illustrate the method with the analysis of Cs_2 data [2] of weakly bound levels of the $6s_{1/2} - 6p_{1/2}$ 0_u^+ and 0_g^- series. We show and characterize many coupled states [3] [4] which are interesting for cold molecule formation.

[1]Photoassociation spectroscopy of $^{87}Rb_2$ $(5s_{1/2} + 5p_{1/2})0_g^-$ long-range molecular states: Analysis by Lu-Fano graph and improved LeRoy-Bernstein formula , H. Jelassi, B. Viaris de Lesegno, and L. Pruvost, Phys. Rev. A **73**, 032501 (2006)

[2]Photoassociation spectroscopy of ultracold Cs below the 6p1/2 limit, M. Pichler, H. Chen and W. C. Stwalley, J. Chem. Phys. 121, 1796 (2004)

[3]Spin effects in $6s_{1/2} - 6p_{1/2}$ 0_u^+ $^{133}Cs_2$ weakly bound molecules analyzed by using the Lu-Fano method coupled to the improved LeRoy-Bernstein formula, H. Jelassi, B. Viaris de Lesegno, and L. Pruvost, M. Pichler, W. C. Stwalley, Phys. Rev. A **78** p. 022503(2008)

[4]Weakly bound $6s_{1/2} - 6p_{1/2}$ 0_g^- Cs_2 levels analysed using the vibrational quantum defect. Detection of two deeply bound $6s_{1/2} - 6p_{3/2}$ 0_g^- levels, L. Pruvost and H. Jelassi, J. Phys. B (accepted).

Sub-Doppler Laser Cooling in Planar Geometries with a Single Laser Beam

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There is huge interest in miniaturizing the technology for ultra-cold atomic physics, particularly for applications concerning sensing. Work towards the achievement of small scale, all-integrated magneto-optical traps (MOT) has been very active, with the realization of MOTs in a microfabricated pyramidal structure [1]. Recently we demonstrated an alternate mirror version of a compact four beam MOT[2].

Here we report on a totally optical planar set-up for laser cooling. Significantly, we have achieved atomic temperatures an order of magnitude lower that the Doppler temperature. Using a triplet of reflection gratings, a single incoming beam is split and steered into three additional parts such that all four beams cross in an almost ideal tetrahedral configuration. This arrangement offers a uniformly balanced radiation pressure area, and allows for efficient sub-Doppler cooling. The planar configuration offers maximal optical access to the atomic cloud and can be easily turned into an integrated micro-trap. In addition, a micro-fabricated tetrahedral configuration offers an ideal tool for a high phase stability optical lattice, with the benefit of fixed lattice geometry.

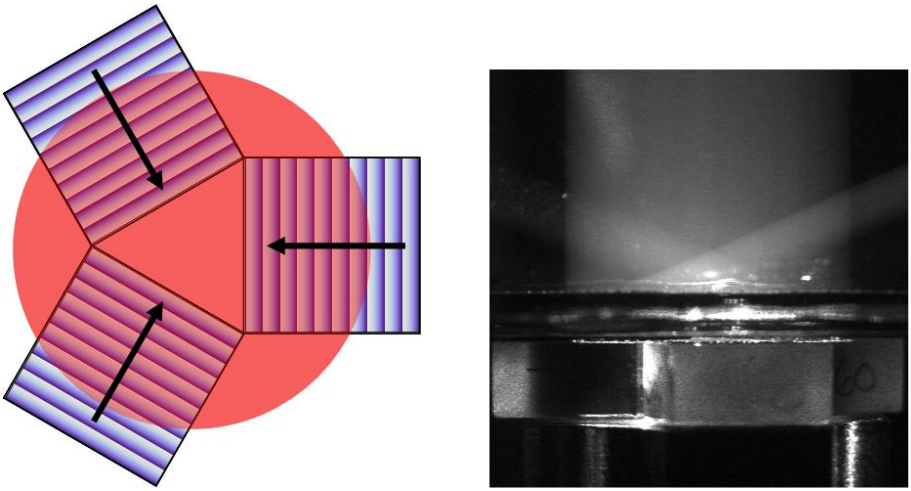

Figure 1: *Left) Schematics of the setup seen from the top. A vertical beam is split and steered using 3 blazed gratings.*
Right) Photograph of setup from the side. The MOT forms in the overlap of the four beams.

[1] S. Pollock, et al., Opt. Express 17, 14109 (2009).
[2] M. Vangeleyn, et al., Opt. Express 17, 13601 (2009)

Laser cooling of Sr atoms on the $^3P_2$ - $^3D_3$ transition at 2.9 μm

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Starting from the long-lived 5s5p $^3P_2$ metastable state, strontium atoms have the 5s5p $^3P_2$ - 5s4d $^3D_3$ cyclic transition at λ = 2.9 μm. When applying the transition to the polarization gradient cooling, its cooling limit can be a few times the photon recoil energy, where the photon recoil energy is as low as 13 nK due to the long wavelength of the transition. Moreover, the transition is of particular interest in view of entangling of atoms using the resonant dipole-dipole interaction [1], because of the long interaction range of $\lambda/2\,\pi \approx 0.5$ μm.

To start with, we developed a frequency stabilized laser at 2.9 μm. A narrow-line 2.9 μm light was generated as an idler frequency by an optical parametric oscillator, where the signal and the pump frequency were stabilized to a fiber-based frequency comb [2] (see Fig. 1). The repetition frequency $f_{\rm rep}$ of the frequency comb was stabilized to a Rb clock with instability of approximately 2 10^{-11} at 1 s, suggesting the laser frequency jitter of the order of 10 kHz at λ = 2.9 μm, which is smaller than the relevant transition linewidth of about 39 kHz [3].

By using the laser, we magneto-optically trapped Sr atoms on the $^3P_2$ - $^3D_3$ transition(see Fig. 2). The temperature of the MOT was measured by a time of flight technique. The temperature of atoms was on the order of μK, which was close to the Doppler cooling limit of this transition. And now, we are trying to polarization-gradient cool this sample in a 3D molasses [4]. By lowering the light shift either by increasing the detuning or decreasing the laser intensity, we expect to achieve tens of nK.

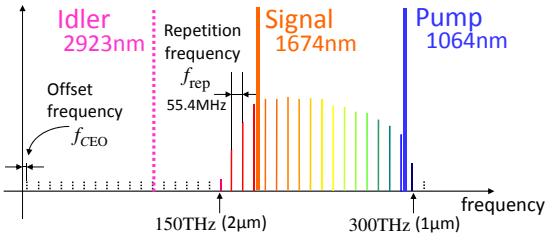

Figure 1: *Schematic for the optical frequency synthesis*

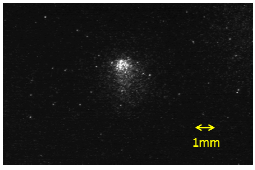

Figure 2: *MOT*

[1]M. Takamoto and H. Katori et al., Phys. Rev. Lett. 102, 063002 (2009).
[2]H. Inaba et al., IEEE J. Quantum Electronics. 40, 7929-936 (2004).
[3]E. N. Borisov et al., Opt. Spektrosk. 63, 475 (1987).
[4]C.Salomon et al., Europhys. Lett. 12,683-688 (1990).

Dynamic Versatility of Hollow Optical Tunnels

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Blue-detuned optical tunnels have been shown to be useful for transporting thermal atoms long distances,[1] as well as for making dividers and delay lines for atomic ensembles that can be modified in real time when created with two-dimensional spatial light modulators.[2] Blue-detuned tunnels have the disadvantage that atoms are not confined absolutely to the axial core; quantum mechanically there are no bound states and classically the tunnels leak. However, the leak can be controlled and made arbitrarily small by setting the ratio between the potential barrier of the tunnel, $k_{\rm B}T_{\rm tun}$, and the kinetic energy of the atoms in the transverse plane, $k_{\rm B}T_a$ sufficiently high, where $k_{\rm B}$ is Boltzmann's constant, T_a the temperature of the atoms and $T_{\rm tun}$ the effective temperature of the tunnel. The tunneling rate in the quantum case is also reduced when $T_{\rm tun} \gg T_a$. On the other hand, the transverse leak can be exploited to cool the ensemble when $T_{\rm tun} \sim T_a$, with no apparent limit preventing the system from reaching the degenerate phase. As we will show in this presentation, these tunnels are very effective at truncating the velocity distribution near $T_{\rm tun}$, which could provide a means for in-transit cooling. At the same time, all-optical light tunnels are an attractive complement to optical lattices for pursuing fundamental studies of cold atoms, e.g., dynamics one-dimensional geometries can be created. The versatility of tunnels constructed with donut-modes (i.e., high-order Bessel and Laguerre-Gaussian) will be discussed.

This work is supported by the National Science Foundation under grant No. PHY-0426696, the Laboratory for Physical Sciences, College Park, MD and the Photonics Technology Access Program (funded by the National Science Foundation and the Defense Advanced Research Projects Agency).

[1]"Long, narrow all-light atom guide," Y. Song, D. Milam and W. T. Hill, III, Opt. Lett. **24** 1805 (1999).

[2]I. Arakelyan, N. Chattrapiban, S. Mitra and W.T. Hill, III, "Versatile element for free-space dividing and redirecting neutral atom clouds," Phys. Rev. A. **75**, R17706 (2007).

Free Space Atom Chips

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All-optical approaches for containing, transporting and manipulating properties of thermal and degenerate atomic ensembles have experienced a dramatic increase in usage over the past decade. Nevertheless, the full advantage of their potential for creating novel, flexible and dynamic elements for atom optics has not yet been realized. All-optical traps can be created and modified in free space and real time, while enabling the atomic ensemble to be well isolated from material surfaces. Combining red-detuned two-dimensional (2D) sheets of light as substrates with red-detuned and/or blue-detuned images embedded as the etched patterns, it is possible to create free-space "atom chips" that could sustain a host of elements for neutral atoms. In this presentation we will describe an adaptation of a phase-contrast approach[1] that has enabled us to generate high-quality optical patterns in the focal plane with a TEM_{00} beam and a 2D phase mask. These optical patterns have substantially less intensity noise than is usually possible with 2D holographic phase gratings. Consequently, these low-noise patterns are ideal candidates to be exploited for creating arbitrary optical potentials for neutral atoms. In contrast to material-based atom chips, free-space atom chips could possess potentials that are exotic, having sharp walls and barriers that could be modified on a timescale commensurate with the flow of an atomic BEC. An update on our progress towards this end will be presented.

This work is supported by the National Science Foundation through a Physics Frontiers Center grant, the Laboratory for Physical Sciences, College Park, MD and the Photonics Technology Access Program (funded by the National Science Foundation and the Defense Advanced Research Projects Agency).

[1]"Generalized phase contrast matched to Gaussian illumination," D. Palima, C. A. Alonzo, P. J. Rodrigo and J. Glckstad, Optics Express Vol. 15, Iss. 19, pp. 1197111977 (2007).

A Miniaturized Planar Microwave Guide for Electrons

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We are currently setting up an experiment aiming at guiding electrons in an AC quadrupole guide. A radially confining potential is formed above a miniaturized planar electrode layout. Similar to the case of planar ion traps, this allows for the realization of complex guiding potentials and high trapping frequencies. In combination with a suited electron source, electron injection near the transverse ground state of motion may become feasible. This would lead to a well defined motional quantum system enabling new experiments involving guided electron interferometry or the controlled interaction of guided electrons.

While ion traps are driven at radiofrequencies, the stable confinement of electrons demands operation at microwave frequencies. We therefore combine the electrode pattern of a microfabricated planar Paul trap with that of a microwave transmission line on a planar substrate. As trapping electrode layout we use a five wire design already used by several groups for ion trapping with a guide to surface distance of $500\,\mu$m. The structure will be driven at frequencies around 1 GHz resulting in a trapping frequency of 100 MHz. For a guide with a length comparable to the wavelength of the driving field, the microwave guiding properties of the electrodes become important. A normal mode decomposition of the structure's transverse field shows that it consists of a superposition of two eigenmodes with different propagation constants. The consequences of the resulting dephasing on the trapping field and possible workarounds will be discussed using numerical particle tracking.

In a first experiment we are implementing an electrically small structure with a length of 20 mm. Electrons with a kinetic energy of 10 eV will be coupled longitudinally to the guide through an aperture. By using a numerically optimized electrode layout a smooth transition from the field free region to the guiding zone is provided. After directing the electrons on a curved trajectory they will be detected on a microchannel plate detector. We will present first experimental results.

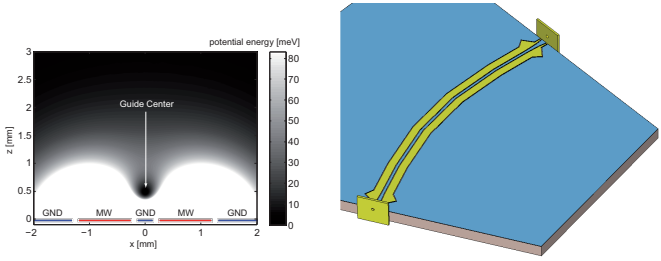

Figure 1: *Left: Transverse cut through the pseudopotential an electron experiences above a five wire structure. Driving and trapping parameters are mentioned in the text. Right: Schematic of the experimental chip layout*

Efficient Two-dimensional Subrecoil Raman Cooling of Atoms in a Tripod Configuration

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The achievement of Bose-Einstein condensation (BEC) by optical means is among relevant problems of laser physics. Optical cooling contributes the bulk of the phase space compression and can be much faster than evaporative cooling, which is of importance for reaching BEC with high atomic density. Using of optical techniques such as Raman cooling allows one to cool an ensemble of Λ-type atoms substantially below the recoil limit in one dimension[1]. At that time, the problem is to extend Raman method over 2D and 3D. We propose a new method of Raman cooling in 2D based on the 2D tripod linkage of atomic states. Tripod schemes are experimentally accessible in metastable Ne, ^{87}Rb, and a number of other gases[2]. The laser configuration of Raman pulses consists of σ_+- and σ_--polarized contra-propagating laser fields and a π-polarized laser field propagating along the perpendicular direction. The advantage of this cooling scheme is wide opportunities of manipulating populations due to the possibility of cooling in two directions at once. As an example, we have demonstrated 2D deeply cooling of atoms with the velocity spread smaller than $0.1\hbar k$ and an efficient temperature lower than $0.01T_{rec}$.

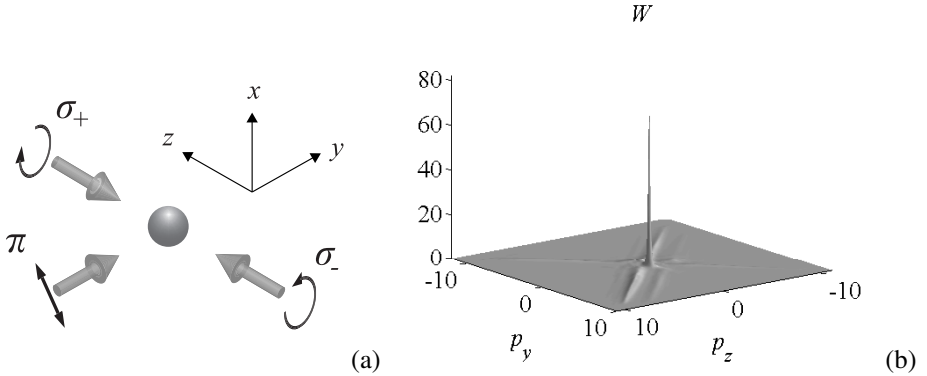

Figure 1: *(a) The geometry of the setup. (b) The velocity distribution after application of the stimulated Raman cooling pulses.*

[1]M. Kasevich and S. Chu, Phys. Rev. Lett. **69**, 1741 (1992).

[2]F. Vewinger, M. Heinz, R. G. Fernandez, N. V. Vitanov, and K. Bergmann, Phys. Rev. Lett. **91**, 213001 (2003).

A 10 μm-period magnetic lattice: optically resolved trapping of ultracold ^{87}Rb atoms in the F=1 state

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Magnetic lattices are a promising alternative to optical lattices and have the potential advantages of low technical noise, low heating rates and highly stable and reproducible potentials [1] [2]. We report here the trapping and cooling of ^{87}Rb atoms in a 1D magnetic lattice constructed from TbGdFeCo magnetic film on a 10 μm-period grooved structure on an atom chip. Previously, ^{87}Rb atoms in the weak field-seeking $|F = 2, m_F = 2\rangle$ state were successfully loaded into the 1D magnetic lattice[1]. Heating due to adiabatic compression in the tight traps and insufficient axial confinement limited the temperature of the trapped atoms to ~ 300 μK and the lifetime to ~ 0.5 s.

Similar experiments have now been performed for ^{87}Rb atoms optically pumped into the $|F = 1, m_F = -1\rangle$ true ground state to eliminate hyperfine changing collisions, to increase the lifetime of the atoms and to reach lower temperatures by evaporative cooling in the lattice. To reduce heating due to adiabatic compression, an improved loading and cooling scheme was implemented: ^{87}Rb $|F = 1, m_F = -1\rangle$ atoms at ~ 30 μK in the Z-wire trap are loaded into a shallower lattice created by the field from the permanent magnetic microstructure and the bias field from the Z-wire current. Evaporative cooling in Z-wire trap then allows $\sim 5 \times 10^5$ atoms to be transferred into about 100 "dimple" traps of the magnetic lattice at a temperature of ~ 10 μK and with a lifetime of ~ 8 s. Under these conditions, and with improved magnification of the detection optics, it is now possible, using in situ absorption imaging, to spatially resolve the individual clouds containing about 5000 ultracold atoms trapped at about ~ 8 μm below the chip surface in the 10 μm-period magnetic lattice (Figure 1).

Future plans include evaporative cooling of the trapped atoms to degeneracy to produce multiple BECs in the magnetic lattice and implementing a 2D magnetic lattice, with periods down to $1 - 4$ μm to perform quantum tunneling experiments in a magnetic lattice.

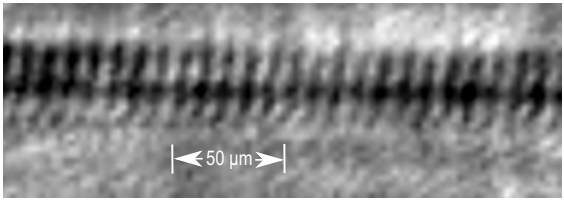

Figure 1: *Sideview absorption image of ^{87}Rb atoms in 10 μm period magnetic lattice*

[1] M. Singh, M. Volk, A. Akulshin, A. Sidorov, R. McLean and P. Hannaford, J. Phys. B. 41, 065301 (2008).
[2] S. Whitlock, R. Gerritsma, T. Fernholz, R. Spreeuw, New J. Phys.11, 023021 (2008).

Towards Raman cooling of a single atom in a tightly focused optical tweezer

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[2]*ETH, Zurich, Switzerland*

Recent experiments have shown that an efficient interaction between a single trapped atom and light can be established by concentrating light field at the location of the atom by focusing [1,2]. However, to fully exploit the benefits of strong focusing one has to pinpoint the atom at the maximum of the field strength. Thus the atomic motion due to the finite temperature obtained after standard laser cooling of the atomic sample must be further reduced. In our experiment a single ^{87}Rb atom is loaded from a Magneto-Optical Trap (MOT) into a tightly focused Optical Dipole Trap (DT) with a depth of $\sim 1\mathrm{mK}$. Subsequent sub-Doppler cooling leads to an average kinetic energy of the atom corresponding to $\sim 20\mu K$. In order to bring the atom to the vibrational ground state of the trap with characteristic frequencies of 20-60 kHz, we implement a Raman Cooling technique similar to the one commonly used in ion traps [3]. Currently we are able to observe the successful transfer of atomic population between the hyperfine ground states of ^{87}Rb atom (see Fig. 1) which is a necessary requirement for Raman cooling.

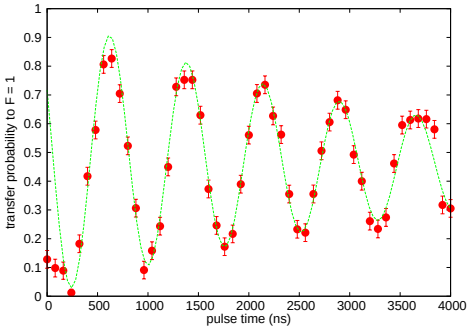

Figure 1: *Population transfer probability between ground hyperfine states of the atom versus duration of Raman pulses.*

However, in the current setup the decoherence time is also on the order of the pulse duration. A better compensation of magnetic fields is required to resolve the vibrational sidebands and further cool the atom to the vibrational ground state of the trap. This should lead to a better localization of the atom in free-space atom-photon interaction experiments. We present current experimental progress towards this goal.

[1] M. K. Tey et. al., New J. Phys. **11**, 043011 (2009)
[2] C. Schuck, et al., Phys. Rev. A, **81**, 011802 (2010)
[3] C. Monroe et al., Phys. Rev. Lett. **75**, 4011 (1995)

Electron bunch shaping with an ultracold plasma

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We demonstrate a method to control the electron density spatial distribution of electron bunches extracted from an ultracold plasma. Coulomb repulsion limits the ultimate charge density and brightness of electron bunches: the Coulomb fields are spatially non-linear and the repulsion cannot be reversed. For ellipsoidal bunches with uniform charge density, the internal fields are linear, allowing refocussing of the expanded bunch. Electron bunches can be generated by photoionisation of a cold atom cloud, offering the unique opportunity to shape the electron density in three dimensions, and so form the required uniform density ellipsoidal bunches.[1] With sufficient brightness and coherence, shaped electron bunches should then enable single-shot diffractive imaging of biological samples. [2]

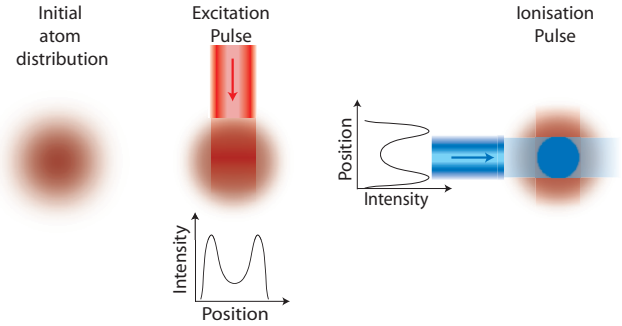

Figure 1: *Scheme for production of uniform density electron bunches. Two-step ionisation allows shaping of the electron bunch in three dimensions via the overlap of the excitation and ionisation laser beams.*

Beginning with a cold atom cloud with Gaussian density distribution, an excitation beam (wavelength 780 nm) with controllable intensity profile excites a fraction of the atoms to an intermediate excited state, shaping the excited atom cloud in two dimensions. The ionisation laser (480 nm), also with shaped intensity profile, photoionises only those atoms in the excited state, along an orthogonal axis. The overlap of the two intensity-shaped laser beams enables shaping of the electron bunch in three dimensions, and hence production of an ellipsoidal bunch with uniform initial density and minimal space-charge emittance growth.

[1] Claessens, B. *et al.*, Cold electron and ion beams generated from trapped atoms, *Phys. Plasmas*, **14** 093101, 2007

[2] S.B. van der Geer *et al.*, Ultracold electron source for single-shot, ultrafast electron diffraction, *Micros. Microanal.* **15** 282, 2009

Loss Mechanism of Superconducting Atom Chips

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We have studied the trapping loss mechanism of the superconducting atom chip which was driven with a persistent current[1]. Firstly we have examined the current distribution in a superconducting wire by measuring the trap height over the applied bias magnetic field (Fig. 1). By comparing with the calculated trap height, the experimental results clearly suggested that there was a penetration of magnetic fluxes into the superconducting wire.

Next we experimentally analyzed the trapping loss rate as a function of the trap height (Fig. 2). The trapping loss rate shows specific curve when the data was taken with the same persistent current, but after washing out the current and re-introducing a persistent current with the same intensity, the loss rate shows a different curve. With these experimental results, we came to understand that the penetrated magnetic fluxes in dendritic pattern locally modified the trapping potential and the Majorana transition loss was introduced [2]. The existence of the dendritic pattern of magnetic fluxes was also proved by an experiment with a novel trap for atoms with a superconducting disc[3].

This research was partly supported by CREST of Japan Science and Technology Agency and KAKENHI of Japan Society for the Promotion of Science.

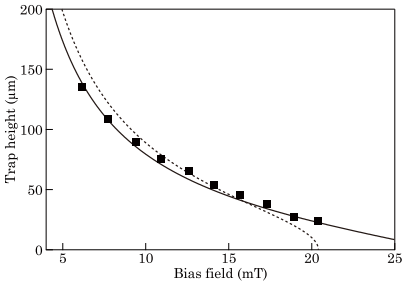

Figure 1: *Trap height vs bias field. The filled squares are experimental data. The solid (dotted) curve represents the trap height calculated with (without) the magnetic fluxes penetration.*

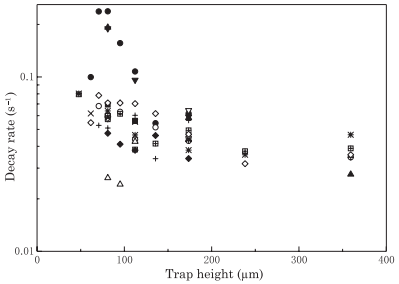

Figure 2: *Decay rate distribution over the trap height. The different symbols indicate data obtained on the different dates. The persistent current was induced a few times per day.*

[1]T. Mukai, C. Hufnagel *et al.*, Phys. Rev. Lett. **98**, 260407 (2007)
[2]C. Hufnagel, T. Mukai, and F. Shimizu, Phys. Rev. A**79**, 053641 (2009)
[3]F. Shimizu, C. Hufnagel, and T. Mukai, Phys. Rev. Lett. **103**, 253002 (2009)

Programmable trap geometries with superconducting atom chips

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[2]*Nanyang Technological University, Singapore*
[3]*Rowan University, Glassboro, New Jersey, USA*

We employ the hysteretic behavior of a superconducting thin film in the remanent state to generate different traps and flexible magnetic potentials for ultra-cold atoms. The strong gradient field for trapping of atoms near a micro-structured surface is provided by quantizied magnetic flux vortices, which are introduced into the superconductor with an external magnetic field and remain after the field removal[1]. The demonstrated traps operate in the mesoscopic limit, so the trapping fields represent an average vortex density rather than individual vortices. Different trap geometries can be programmed by appropriately chosen sequences of applied fields, which imprint spatial magnetic patterns on the thin film. This new approach for atom-optics is demonstrated by three different trap types realized on a single micro-structure: a Z-type trap, a double trap and a bias field free trap. Our studies show that superconductors in the remanent state provide a new versatile platform for atom-optics and applications in ultra-cold quantum gases.

[1]T. Müller, B. Zhang, R. Fermani, K.S. Chan, Z.W. Wang, Z.B. Zhang, M.J. Lim, R. Dumke, New J. Phys. **10**, 043016 (2010)

Superfluid/feromagnet/superfluid-junction and π-phase in a spin-polarized Fermi gas

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[3]*CREST(JST), Honcho, Saitama, Japan*

We discuss a possible idea to introduce an superfluid/ferromagnet/superfluid (SFS) -junction to a superfluid Fermi atomic gas. To explain our idea in a simple manner, we consider a two-component spin-polarized Fermi superfluid at $T = 0$, described by a one-dimensional attractive Hubbard model, where two atomic hyperfine states are described by pseudospin $\uparrow$ and $\downarrow$. When this polarized Fermi superfluid is put in a double-well potential shown in Fig.1(a), some of excess atoms are shown to be localized around the central barrier, so that the superfluid phase is spatially separated by the wall of excess atoms. (See Fig.1(b).) When we interpret the excess atoms localized around the central barrier as a ferromagnetic wall of $\uparrow$-pseudospins, this system looks like a superconductor/ferromagnet/superconductor(SFS)-junction in metallic superconductivity. Indeed, as discussed in the superconducting SFS-junction, Fig.1(c) shows that the so-called π-phase is also realized in the present case, where the superfluid order parameter changes its sign across the junction. Our results would be useful for the study of magnetic effects on Fermi superfluids using superfluid Fermi gases. This work is supported in part by a Grant-in-Aid for the Global Center of Excellence for High-Level Global Cooperation for Leading-Edge Platform on Access Spaces from the Ministry of Education, Culture, Sport, Science, and Technology in Japan.

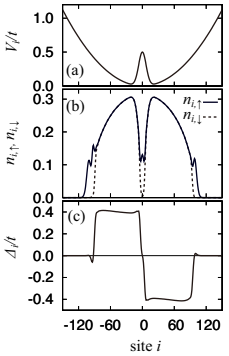

Figure 1: *(a) Model double-well potential V_i, normalized by nearest neighbor hopping t. The x-axis shows the lattice site i in the one-dimensional Hubbard model. (b) Calculated density profiles, $n_{i,\uparrow}$(solid line), $n_{i,\downarrow}$(dashed line), for pseudospin $\uparrow, \downarrow$, respectively. (c) Spatial variation of the superfluid order parameter Δ_i. In this culculation, we set $N_\uparrow = 47, N_\downarrow = 43$.*

Structure factor of a strongly interacting Fermi gas

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ACQAO, Swinburne University of Technology, Hawthorn, 3122 Victoria, Australia

Universality is a striking feature of strongly interacting Fermi gases. For sufficiently strong interactions, all dilute Fermi systems behave identically on a scale given by the average particle separation. The Tan relations[1] are a set of exact universal results applicable to the Bose-Einstein condensates (BEC) and Bardeen-Cooper-Schrieffer (BCS) crossover, based on a single short range parameter known as the contact $\mathcal{I}$. The spin-antiparallel static structure factor, $S_{\uparrow\downarrow}$, of a Fermi gas in the BEC-BCS crossover also depends on the contact [2]:

$$S_{\uparrow\downarrow}(q \gg k_F) = \frac{\mathcal{I}}{4Nk_F}\frac{k_F}{q}(1 - \frac{4}{\pi qa}) \tag{1}$$

where N is the atom number, k_F is the Fermi momentum, q is the probe momentum and a is the s-wave scattering length.

This simple power law shows how the structure factor depends on momentum. Bragg spectroscopy is performed on a strongly interacting Fermi gas of ^{6}Li atoms in the two lowest spin states to experimentally measure the structure factor[3]. Figure 1 below shows both the measured and calculated structure factor as a function of the inverse momentum k_F/q for three interaction strengths $1/k_Fa$ = 0.3, 0.0, -0.2. We have also investigated the temperature dependence of the structure factor and contact for $1/k_Fa$ = 0 over the temperature range 0.1 $\rightarrow$ 1.0 T/T_F, providing a temperature dependent picture of pairing in unitary Fermi gases.

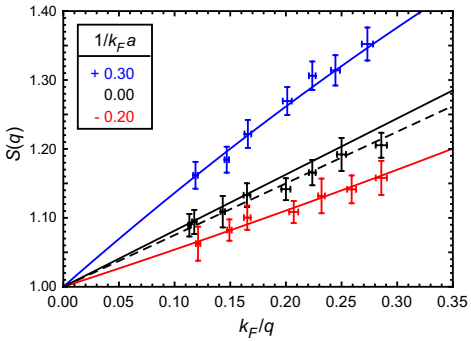

Figure 1: *Universal behaviour of the structure factor of a strongly interacting Fermi superfluid. Measured and calculated static structure factor versus* k_F/q.

[1] S. Tan, Ann. Phys. **323**, 2952 (2008); **323** 2971 (2008); **323** 2987 (2008)
[2] H.Hu, Arxiv:1003.3511v1 (2010)
[3] G. Veeravalli *et al.*, Phys. Rev. Lett. **101**, 250403, (2008), H.Hu *et al.*, Arxiv:1001.3200 (2010)

Universal thermodynamics and critical behaviour in one-dimensional strongly interacting fermions

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[3]*ACQAO and Nonlinear Physics Centre, Research School of Physics and Engineering, Australian National University, Canberra ACT 0200, Australia*

We demonstrate the universal thermodynamics and criticality of one dimensional (1D) interacting fermions with $SU(N)$ symmetry. Not only do these systems continue to inspire significant developments in mathematics and physics, they are also highly relevant to many current cold atom experiments. Using exact results, we elucidate the pairing phenomena and quantum phase transitions in these fermion systems.

For spin-1/2 Fermi gas with attractive interaction, we prove that there are three quantum phases: the fully paired phase which is a quasi-condensate with zero polarization, the fully polarized (normal) phase with $p = 1$, and the partially polarized (1D FFLO) phase where $0 < p < 1$ at zero temperature [1]. Our prediction of the phase diagram of this system was recently confirmed experimentally by Hulet's group at Rice University [2]. Moreover, at low temperatures, the physics of the gapless phase belongs to the universality class of a two-component Tomonaga-Luttinger liquid (TLL) [3]. The peak shape of compressibility in the tails of trapped fermions provides precise measurement of temperature and criticality.

For 1D attractive Fermi gas with $SU(N)$ symmetry, we have made a breakthrough in obtaining the low temperature thermodynamics of the system for arbitrary Zeeman splitting [4]. These results open up many new directions, including multi-component TLL phases and their critical behaviour caused by population imbalances.

[1]X.-W. Guan, M. T. Batchelor, C. Lee and M. Bortz, Phys. Rev. B **76**, 085120 (2007).
[2]Y. Liao, et al, *Spin-Imbalance in One-Dimensional Fermi Gas*, Nautre (2010), in press.
[3]E. Zhao, X.-W. Guan, W. V. Liu, M. T. Batchelor and M. Oshikawa, Phys. Rev. Lett. **103**, 140404 (2009).
[4]X.-W. Guan, M. T. Batchelor, C. Lee and H.-Q. Zhou, Phys. Rev. Lett. **100**, 200401 (2008).

Three repulsively interacting fermions in harmonic traps: Exact solution, ferromagnetism, and high-temperature thermodynamics

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Three fermionic, strongly repulsively interacting atoms in a spherical harmonic trap constitutes the simplest nontrivial system that may exhibit the interesting itinerant ferromagnetism. Here, we present a complete set of exact solutions of three trapped, interacting fermions near a Feshbach resonance and analyse energy levels on the upper branch of the resonance, where atoms should interact repulsively. We find that three fully polarized fermions are energetically stable against a single spin flip when the positive s-wave scattering length a is sufficiently large, indicating the possibility of itinerant ferromagnetism. We analyse as well energy levels on the lower ground-state branch of the resonance, where a molecule of size a forms. The whole energy spectrum, including the lower and upper branches, shows a series of apparent avoided crossings close to resonance when plotted as a function of the scattering length a. These avoided crossings may lead to nontrivial consequences in the time-dependent field-sweep experiment passing from the weakly interacting regime at $a = 0^+$ to the unitarity limit at $a = +\infty$. We demonstrate how to obtain high-temperature thermodynamics of a strongly repulsive (and attractive) Fermi gas by developing a quantum virial expansion method. The second and third expansion (virial) coefficients are calculated using the knowledge of exact solutions of three particles. The resulting equations of state, such as energy and entropy as a function of temperature, confront future experimental measurements. Our results of thermodynamics may also provide a useful benchmark for future quantum Monte Carlo simulations performed at high temperatures.

Collective Oscillations in Bose-Fermi Mixtures at Finite Temperature in Time-Dependent Approach

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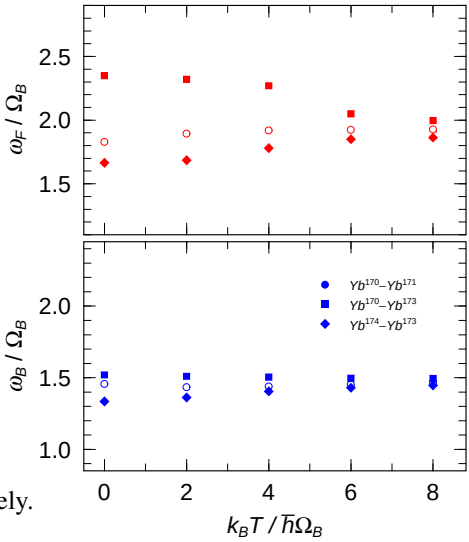
Recently Kyoto group has succeeded to realized the bose-fermi mixtures with Yb isotopes and is making experiments on collective oscillations of these systems.

In the previous works we study the collective monopole[1], dipole[2] and quadrupole motions[3] of the bosons and fermion mixture at zero temperature by solving the time-dependent Gross-Pitaevskii equation and the Vlasov equation. In these works the fermion oscillation show complicated behaviors by including three mode, the volume oscillation mode, the surface vibration modes and the forced vibration mode.

In this work we extend our transport model to describe systems at finite temperature; we introduce the thermal bosons and two body collisions and describe their time evolutions in the VUU equation.

We choose three kinds of combinations, ^{170}Yb$-^{171}$Yb , ^{170}Yb$-^{173}$Yb and ^{174}Yb$-^{173}$Yb , where boson-fermion interactions are weakly repulsive, strongly attractive and strongly repulsive, respectively. Using out time-depedent approach, then, we investigate the quadrupole oscillation of the Yb-Yb system, where the number of the bosons and the fermions are taken to be 10,000 and 1,000, respectively.



In Figure we show the quadrupole frequencies as functions of the temperature. The frequencies and temperature are scaled with the trap frequencies, Ω_B.

We can see that the frequencies of the fermion oscillation approach a certain value with the increase of the temperature as well as the boson frequencies. We will investigate the damping behavior caused by the collisions.

[1] T. Maruyama, H. Yabu and T. Suzuki, Phys. Rev. **A72**, 013609 (2005).
[2] T. Maruyama and G.F. Bertsch, Phys. Rev. **A77**, 063611 (2008).
[3] T. Maruyama and H. Yabu, Phys. Rev. **A80**, 043615 (2009).

BCS-BEC Evolution and Majorana Zero Modes in p-wave Resonant Fermi Gases

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There has recently been intense interest on superfluidity in spin-polarized Fermi gases. Chiral p-wave superfluidity which breaks time-reversal symmetry is highly expected to be realized in this system near a p-wave Feshbach resonance induced by sweeping magnetic field in ^{6}Li. It has been predicted that the p-wave superfluid undergoes the BCS-to-BEC topological phase transition and the BCS regime is associated with the non-trivial topological number which implies the non-trivial quasiparticle excitation due to the chirality of p-wave pairing[1]. The noticeable consequence is that the lowest energy of the quasiparticles can be exactly zero when the quantized vortex with an odd number vorticity exists. Since the zero energy quasiparticle is composed of the equivalent contributions from the particle and hole excitations, its creation is describable with a self-Hermitian operator, called the Majorana fermion. As a consequence of the self-Hermitian, their host vortices obey neither Fermi nor Bose statistics, called the non-Abelian statistics[2].

Here, we propose that the ultracold Fermi gas can be one of the base platform to realize various theoretical issues on the Majorana zero modes. In the weakly attractive interacting regime, the fermionic atoms form p-wave Cooper pairs, while p-wave molecules undergoes Bose-Einstein condensation in the strong coupling regime. In contrast to the BCS-BEC crossover in s-wave resonant gases, two regimes are differentiated by the topological phase transition. It is demonstrated here that the Majorana zero modes only exist in the BCS side of the topological phase transition[3] and the characteristics of the Majorana zero modes drastically changes even in the BCS phase[4]. Furthermore, the quasiparticle tunneling between neighboring vortices is discussed analytically and numerically. It is found that the quasiparticle tunneling splits the degeneracy of the Majorana zero modes[5], which gives rise to the decoherence of the topological qubit composed of the Majorana zero modes. Throughout this work, it is concluded that the stability of the Majorana zero modes is closely linked to the BCS-to-BEC topological phase transition which occurs in the vicinity of a p-wave Feshbach resonance.

[1] N. Read and D. Green, Phys. Rev. B **61**, 10267 (2000).
[2] C. Nayak, S.H. Simon, A. Stern, M. Freedman, S. Das Sarma, Rev. Mod. Phys. **80**, 1083 (2008).
[3] T. Mizushima, M. Ichioka, and K. Machida, Phys. Rev. Lett. **101**, 150409 (2008).
[4] T. Mizushima and K. Machida, Phys. Rev. A **81**, 053605 (2010).
[5] T. Mizushima and K. Machida, arXiv:1005.4738.

Physics of SU(3) cold atom gases: crystallization and color-charge separation

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[1]*Instituto de Estructura de la Materia - CSIC, Madrid, Spain*
[2]*Karlsruhe Institute of Technology, Germany*
[3]*Princeton University, USA*

We discuss the physics of cold fermionic atoms with different hyperfine states with SU(3) symmetry confined in one-dimensional optical lattices. We concentrate on two interesting phenomena that we study through DMRG simulations: The crystallization of trions and color-charge separation.

Trions are strongly bound states of three fermions. Atomic density waves appear in these systems and are pinned due to the confining potential that traps the atoms. We show that this crystalline phase is generic in the presence of the trap due to its incompressibility and is robust agains anisotropy of the interaction. We show the crossover between trionic superfluid and the crystal phase as a function of the interaction and as a function of the anisotropy of the interaction [1].

Color-charge separation generalizes the conventional spin charge separation for interacting SU(2) fermions in one dimension. Through time-dependent DMRG simulations, we explore the features of this phenomenon. In our numerical simulations of finite size systems, we observe different velocities of the charge and color degrees of freedom when a Gaussian wave packet or a charge (color) density response to a local perturbation is evolved. The differences between attractive and repulsive interactions are explored and we note that neither a small anisotropy of the interaction, breaking the SU(3) symmetry, nor the filling impedes the basic observation of these effects [2].

[1]R.A. Molina, J. Dukelsky, P. Schmitteckert, Phys. Rev. A **80**, 013616 (2009).
[2]T. Ulbricht, R.A. Molina, R. Thomale, P. Schmitteckert, ArXiv:1002.3685.

Confining potential approaches to low energy scattering

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School of Engineering, Charles Darwin University, Darwin NT 0909, Australia

The computational technicalities associated with solving scattering problems are known to be more involved than solving bound state problems. For this reason, quasi-bound state approaches, such as the various R-matrix methods have often been applied to the solution of scattering problems.

We discuss how artificial confining potentials can be added to a scattering Hamiltonian to convert a variety of low energy scattering problems to bound state problems. The confining potentials that are added are polynomial potentials of the type $V_{\rm CP}(r) = Gr^n$. Potentials of this type do not have an abrupt wall and thus can be used with correlated basis sets sometimes used in few-body physics. The basis sets used in the present applications are explicitly correlated Gaussians.

The confining potential approach has been applied to a number of few body scattering systems. Scattering information can then be extracted by a variety of approaches depending on the specific nature of the problem at hand. Results will be presented for some standard problems such as low energy electron(positron)-scattering from helium, In other cases, results will be presented for problems that have so far been inaccessible to standard approaches. These include the prediction of the positron annihilation cross section in the scattering of thermal electrons from the hydrogen molecule and the prediction of the pick-off annihilation cross section for ortho-positronium annihilation in helium.

The confining potential approach is not restricted to atomic problem and can also be applied to other systems such a low energy nuclear scattering. The competitive advantage of the method is greatest for difficult systems, such as those with strong projectile-target correlations or those with a composite particle with internal structure as the projectile.

Efimov physics in 3-component lithium 6

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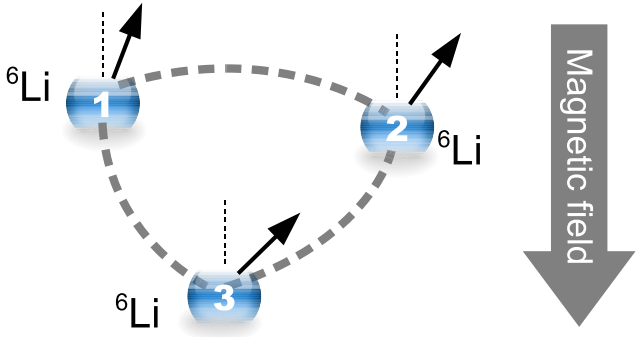
Remarkable universal properties of the three-body systems with very strong short-range interaction (close to unitarity) were predicted forty years ago by nuclear physicist Vitaly Efimov, in particular the existence of universal 3-body bound states whose binding mechanism cannot be explained classically.

A few years ago the existence of those states were finally observed in cold atomic gases. In particular, the case of a 3-component fermionic lithium 6 gas revealed several interesting Efimov features[1] which we analysed[2]. While those features are qualitatively consistent with the universal predictions, they also present some non-universal deviations. We recently investigated those non-universal deviations experimentally and theoretically [3] in the case of single atoms and dimers which are resonant with Efimov states.



[1]T. B. Ottenstein et al., Phys. Rev. Lett. 101, 203202 (2008). J. H. Huckans et al., Phys. Rev. Lett. 102, 165302 (2009).

[2]P. Naidon and M. Ueda, Phys. Rev. Lett. 103, 073203 (2009).

[3]S. Nakajima, M. Horikoshi, T. Mukaiyama, P. Naidon, and M. Ueda, arXiv:1003.1800 (2009).

Non-universal Efimov Atom-Dimer Resonances in a Three-Component Mixture of ^{6}Li

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Since the first experimental evidence of Efimov states in an ultracold cesium atomic gas [1], few-body physics in ultracold atoms has attracted growing interest. The observation of 3-body and atom-dimer loss peaks and dips confirmed the very general properties of few-body systems near unitarity such as the universal scaling laws associated with the existence of Efimov states. Although these loss enhancements and recombination minima are qualitatively explained by the universal theory (UT), their positions are shifted from those of the universal predictions.

We observed an enhanced atom-dimer loss due to the existence of Efimov states in a three-component mixture of ^{6}Li atoms. We measured the magnetic-field dependence of the atom-dimer loss in the mixture of atoms in state $|1\rangle$ and dimers formed in states $|2\rangle$ and $|3\rangle$, and found two peaks corresponding to the degeneracy points of the energy levels of $|23\rangle$ dimers and the ground and first excited Efimov trimers. We found that the locations of these peaks disagree with universal theory predictions, in a way that cannot be explained by non-universal 2-body properties. We constructed theoretical models that characterize the non-universal 3-body physics of three-component ^{6}Li atoms in the low energy domain[2]

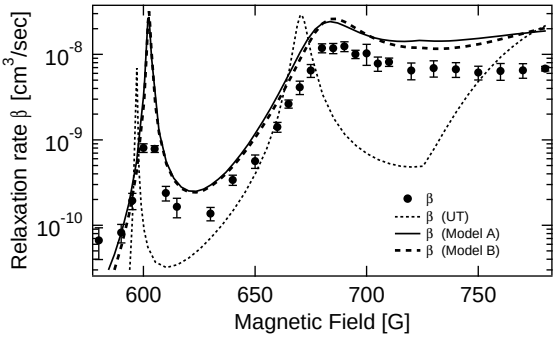

Figure 1: *Magnetic-field dependence of the atom-dimer loss coefficient β (filled circles) in a mixture of atoms in state $|1\rangle$ and dimers of $|23\rangle$. The dotted curve is the calculated β from UT. The solid curve and the dashed curve show the β values calculated from our non-universal models A, B respectively.*

[1]T. Kraemer *et.al.*, Nature **440**, 315 (2006)
[2]S. Nakajima *et.al.*, arXiv:1003.1800.

Confinement-induced resonance in quasi-one-dimensional systems under transversely anisotropic confinement

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It was observed recently by Haller[1] that a strongly interacting quasi-one-dimensional quantum gas of Cs atoms under transversely anisotropic confinement exhibits a splitting of the confinement-induced resonance. With increasing transverse anisotropy, the position of one resonance shows a pronounced downshift, while another shifts up slightly. The present paper investigates theoretically the confinement-induced resonance as a function of transverse anisotropy for a model of simple two-body *s*-wave scattering. In contrast with the experimental finding, we find a single resonance only, whose position is in excellent agreement with the observed downshifted resonance. We propose that the second, upshifted resonance found in the experiment may be caused by higher angular momentum effects, possibly a d-wave resonance.

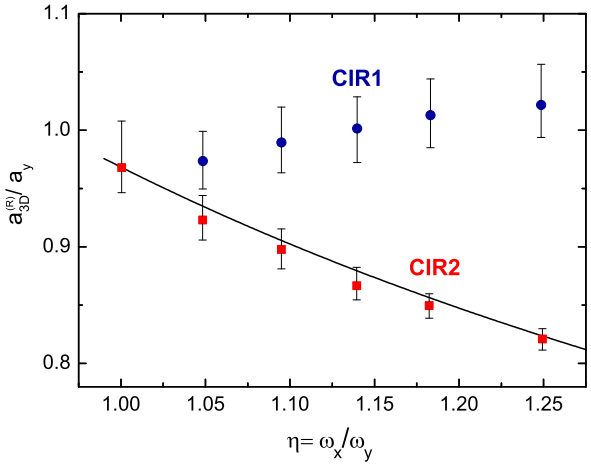

Figure 1: *Resonance positions of CIRs, $a_{3D}^{(R)}$, as a function of the transverse anisotropy $\eta = \omega_x/\omega_y$. The experimental results (symbols) are compared with our s-wave scattering prediction (solid line)*[2].

[1]E. Haller et al., Physical Review Letters 104, 153203 (2010).
[2]arXiv:1005.2794v1

A Bose-Einstein condensate coupled to a micromechanical oscillator

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[3]*Laboratoire Kastler Brossel, E.N.S, Paris, France*
[4]*University of Basel, Basel, Switzerland*

Ultracold atoms can be trapped and coherently manipulated close to a surface using chip-based magnetic microtraps on so-called atom chips. This opens the possibility of studying interactions between atoms and on-chip solid-state systems such as micro- and nanostructured mechanical oscillators. Such oscillators have attracted attention due to the extreme force sensitivity and the novel manipulation techniques of cavity optomechanics. The question is raised whether the toolbox for quantum manipulation of ultracold atoms could be employed to read out, cool, and coherently manipulate the oscillators state. Several theoretical proposals show that sufficiently strong and coherent coupling between atoms and oscillators would enable studies of entanglement, quantum state transfer, and quantum control of mechanical force sensors.

In our experiment[1] we demonstrate a first step in this direction and couple the vibrations of a micromechanical cantilever to the collective motion of Bose-condensed atoms in a trap. The interaction relies on surface forces experienced by the atoms at about 1 μm distance from the cantilever. We observe resonant coupling to several well-resolved mechanical modes of the condensate, including in particular the center of mass mode and the breathing mode. We use trap loss as the simplest way to detect the atomic motion induced by the coupling. With this method we are able to sense cantilever oscillations with a minimum resolvable amplitude of 13 nm, limited by the atomic trap lifetime and trap anharmonicity.

Coupling via surface forces does not require magnets, electrodes, or mirrors on the oscillator and could thus be employed to couple atoms to molecular-scale oscillators such as carbon nanotubes.

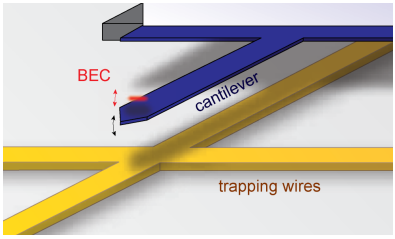

Figure 1: *Microcantilever integrated on an atom chip.*

[1]D. Hunger *et al.*, PRL **104**, 143002 (2010)

A Cavity Optoelectromechanical System for Quantum Physics, Sensing, and Metrology.

J. Knittel, T. G. McRae, G. I. Harris, K. H. Lee, W. P. Bowen

University of Queensland, Brisbane, OLD, Australia

Cavity optomechanical systems offer the potential to test quantum mechanical properties of macroscopic systems. This technology could have important ramifications across diverse areas; from fundamental physics such as tests of quantum gravity, quantum nonlinear mechanics, and gravitational wave detection; through to applications in optically driven photonic circuits, quantum information science, and ultra-sensitive mass, force, and spin sensors.

Two key requirements to enter the quantum regime are the capacity for quantum control of the cavity optomechanical system and the ability to achieve zero-point motion limited transduction sensitivity. Strong electrical actuation of mechanical oscillators, an essential step for quantum control, has been achieved in nano-electromechanical systems; while transduction sensitivities near the quantum limit have recently been reached with cavity optomechanical systems.

In this poster we report the first experiments integrating these two capabilities into a single cavity opto-electro-mechanical system[1], using a micro-toroidal whispering gallery mode resonator. A strong electrical field gradient is generated by a sharp tip that is placed over the micro-toroid cavity, which is made of silica. Measurements of the change in transduction signal with the probe height and applied DC voltage showed that the intrinsic polarization of the silica is the origin of the resonators mechanical response to the gradient field.

We achieved electrical gradient induced actuation forces as large as 0.40 μN. These actuation forces do not result in significant heating and have significantly higher magnitude than what has been achieved with cryogenically compatible radiation pressure actuation. Simultaneously, we measured a mechanical transduction sensitivity below $10^{-18}\frac{m}{\sqrt{Hz}}$, representing a 3 orders of magnitude improvement over any other nano-electromechanical system to date.

By lateral scanning of the drive electrode similar to a scanning probe microscope, we were able to image the mechanical mode structure of our micro-toroid cavity . This new imaging technique allowed experimental confirmation of the mechanical mode shapes of our micro-cavity and gives a spatial profile that is in agreement with finite element modeling.

[1]K. H. Lee, T. G. McRae, G.I. Harris, J. Knittel and W. P. Bowen, "Cooling and control of a cavity optoelectromechanical system.", Physical Review Letters 104 123604 (2010).

Cooling and Control of a Cavity Opto-Mechanical System using Electric Fields

J. Knittel[1], G. I. Harris[1], T. G. McRae[1], K. H. Lee[1], W. P. Bowen[1]

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Simple harmonic oscillators provide a quintessential example of the profound difference between classical and quantum mechanics. Their quantum behavior has been observed in many analog systems. However, for true macroscopic mechanical oscillators the quantum regime remains an elusive challenge. Advanced refrigeration and control techniques are required to freeze out the usually dominant thermal fluctuations, and ultra-sensitive transduction is required to resolve the oscillators quantum zero-point fluctuations. For a typical microfabricated mechanical oscillator this necessitates μK temperatures, and 10^{-17}m transduction resolution.

Rapid progress in this direction is underway in cavity optomechanical systems and nanoelectromechanical systems. Cavity optomechanical systems have superior mechanical transduction sensitivity, and are able to resolve mechanical zero-point fluctuations. However, the electrical actuation of nanoelectromechanical systems provides far greater scope for quantum control and cooling.

We have combined these two capabilities into a single cavity optoelectromechanical system with transduction sensitivity surpassing the current state-of-the-art in nanoelectromechanical systems by two orders of magnitude[1].

Our system consists of a toroidal microcavity that is placed in a strong electromagnetic field gradient. By modulating the electric field gradient via a feedback control loop we actively damp one of the thermally activated mechanical vibration modes of the cavity. Using this system we have achieved for the first time active cooling of a cavity optomechanical system with an electric field gradient. The final temperature is limited to 60 K by optical shotnoise. An additional probe field at a different wavelength provided an out-of-loop mechanical transduction that yielded an independent temperature verification, and thus a direct comparison between temperature measurements deduced from in-loop and out-of-loop signals. As expected stark differences are observed, with serious over-estimation of cooling via the standard in-loop signal. Finally, we will discuss the route to ground-state cooling with this system.

[1]K. H. Lee, T. G. McRae, G.I. Harris, J. Knittel and W. P. Bowen, "Cooling and control of a cavity optoelectromechanical system.", Physical Review Letters 104 123604 (2010).

Nonlinear phenomena in a quantum many-body nano-electromechanical system

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In this presentation we consider a superconducting microwave resonator containing n nano-mechanical resonators. The nano-mechanical resonators are not directly coupled to one another, but are all coupled to the microwave cavity field. This coupling is between the photon number of the microwave cavity field, and the position quadrature of each nano-mechanical resonator. Both the microwave and the mechanical systems are dissipative. Different behaviour arises with different nano-mechanical frequencies and field couplings. We show that identical nano-mechanical oscillators form a single collective mechanical mode which couples to the microwave cavity with a strength dependent on the square sum of the individual mechanical-microwave couplings. Classically, we show this system has a rich fixed point bifurcation structure which is also dependent on a collective mechanical coordinate, even for non-identical nano-mechanical resonators. We comment on the quantum signatures of the semi-classical bifurcations. We also show, in the adiabatic limit approximation of the microwave resonator, that the nano-mechanics are governed by an effective potential with an anharmonic term that is the arctangent of a displaced collective mechanical coordinate. We will present the signatures measurable in the microwave cavity field of these interesting nonlinear phenomena.

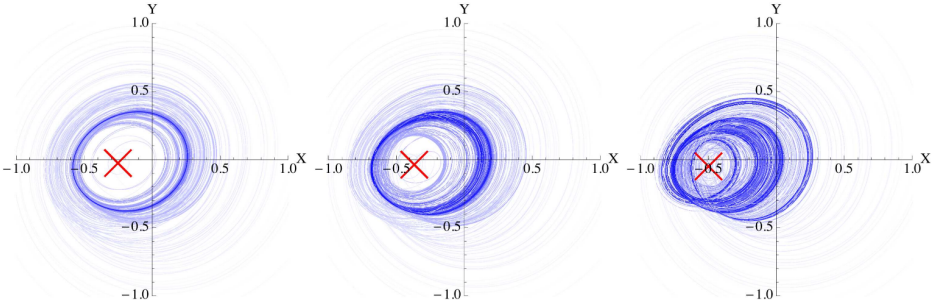

Figure 1: *(Colour online) Some bifurcations of the nano-electromechanical system. Here we show period doubling to chaos for three linearly increasing microwave cavity detunings. The plots show semi-classical trajectories (from light blue to dark blue with increasing time) in the phase plane of the collective mechanical coordinate. The red cross is an unstable fixed point of the system. As well as the chaos shown here, the system also exhibits Hopf and saddle-node bifurcations for different transitions in parameter space.*

Brownian Motion of a Microsphere Cantilever

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Cavity optomechanics has drawn dramatic attention over the past five years due to promises it offers of studying quantum mechanical effects on macroscopic systems. Dynamical backaction cooling of the optomechanical devices makes displacement sensors with a sensitivity approaching the standard quantum limit possible[1]. Cavity enhanced optical forces are also very promising for building all-optical controlled switches and filters in photonic circuits[2]. We have successfully fabricated micropendulums or cantilevers made from a microsphere attached to a tapered fibre stem as alternative devices for studying cavity optomechanics.

In our experiment, light is coupled into and out of the microsphere through a tapered optical fibre. Transmitted light is detected by a photodiode and a fast Fourier transform (FFT) of the photocurrent of the photodiode is used to analyse the mechanical modes of the microsphere cantilever. Brownian motion of the cantilever has been observed when the wavelength of the probe light was tuned to the blue side of resonance (Fig. 1). The frequencies of the harmonics are (1) 130, (2) 260, (3) 390, (4) 520 (5) 650 and (6) 780 Hz respectively. The spikes with frequency lower than 100 Hz could be environmental noise.

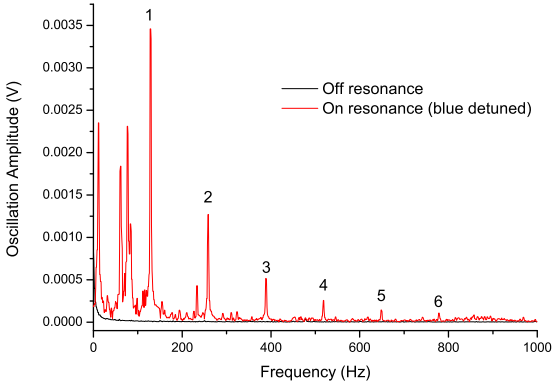

Figure 1: *Mechanical modes spectrum when the probe light is off resonance (black curve) and slightly blue detuned from the resonance (red curve)*

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[1]T. J. Kippenberg and K. J. Vahala, "Cavity Opto-Mechanics", Opt. Express **15** 17172 (2007)

[2]J. M. Ward, Y. Wu, V. G. Minogin, and S. Nic Chormaic, "Trapping of a microsphere pendulum resonator in an optical potential", Phys. Rev. A **79**, 053839 (2009)

A numerical study of few-photon ionization processes in Helium using the Pyprop framework

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Few-photon induced breakup of Helium is studied using a newly developed *ab initio* numerical framework for solving the six-dimensional time-dependent Schrödinger equation[1]. We present details of the method and generalized cross sections for the process of two-photon nonsequential (direct) double ionization at photon energies ranging from 39.4 to 54.4 eV, a process that has been very much debated in recent years and is not yet fully understood. In particular, we have studied the convergence property of the total cross section in the vicinity of the upper threshold (~ 54.4 eV): versus the pulse duration of the applied laser field. We find that the cross section exhibits an increasing trend near the threshold, as has also been observed by others, and show that this rise cannot solely be attributed to an unintended inclusion of the sequential two-photon double ionization process, caused by the bandwidth of the applied field[2].

Finally, we investigate the angular dependence of single- and double ionization from excited states in Helium. A similar case was recently investigated experimentally for excited Lithium, where variations in the double ionization probability, as a function of the angle between the field and the aligned (2p) atom[3]. Since the electrons in Helium are more strongly correlated, a greater angle sensitivity may be expected in the ionization yields.

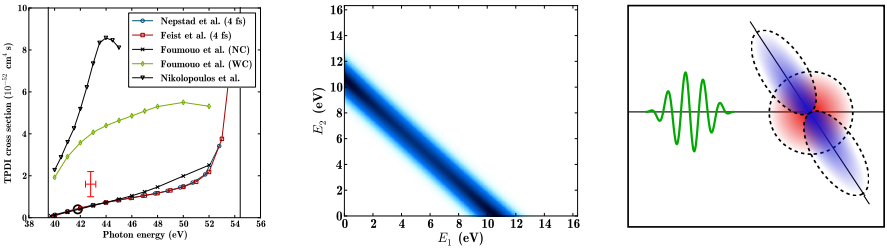

Figure 1: *Left: Generalized cross sections for two-photon double ionization of Helium. Center: Electron energy distribution at 44.9 eV photon energy. Right: Excited aligned Helium exposed to xuv radiation.*

[1]T. Birkeland and R. Nepstad, `Pyprop`, *http://pyprop.googlecode.com*
[2]R. Nepstad, T. Birkeland and M. Førre, Phys. Rev. A, in print (2010)
[3]G. Zhu *et al.*, Phys. Rev. Lett 103, 103008 (2009).

Above-threshold ionisation of atomic hydrogen using few-cycle pulses

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F. G. Hanne[3],
A. N. Grum-Grzhimailo[4], B. Abeln[4], K. Bartschat[4],
I. Ivanov[5], A. Kheifets[5],
H. M. Quiney[6],
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[3]*Atomic and Electronics Physics Group, Westfalische Wilhelms-Universitat, Munster, Germany*
[4]*Department of Physics and Astronomy, Drake University, Des Moines, Iowa, USA*
[5]*Research School of Physical Sciences, The Australian National University, Canberra, Australian Capital Territory, Australia*
[6]*ARC Centre of Excellence for Coherent X-Ray Science, University of Melbourne, Melbourne, Australia*

We present data from the first ever experiment on atomic hydrogen (H) using few-cycle pulses. The few-cycle laser system of the Australian Attosecond Science Facility produces linearly polarised, $\sim$6 fs pulses at 800 nm with energy of $\sim$100-200 μJ, which are focused into the atomic beam using an off-axis parabolic mirror. We use intensities of $1 - 6 \times 10^{14}$ W cm^{-2} to induce above-threshold ionisaion (ATI) in the H beam and detect the ejected photoelectrons with energies above the cutoff set by a repeller plate.

Experimental data are compared to different theoretical approaches: the standard strong field approximation (SFA) and direct numerical integration of the 3D Schrödinger equation on a grid (TDSE). Results show that the SFA is inadequate when quantitative agreement between experiment and theory is desired. However, the TDSE shows agreement with the experimental data at the 20% level set by experimental error.

We will present benchmark data for above threshold ionisation using few-cycle laser pulses. We use the most simple atomic system which can be used as a quantitative test for state of the art theoretical models of light-matter interactions.

High Resolution Imaging of Mott Insulator Shells

C. Weitenberg[1], J.F. Sherson[2], M. Endres[1], M. Cheneau[1], R. Glöckner[1], R. Labouvie[1], I. Bloch[1,2], S. Kuhr[1]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*
[2]*Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 München, Germany*

Ultracold quantum gases in optical lattices have evolved in the last years into an interdisciplinary tool for many-body solid state and quantum physics. To fully exploit the possibilities of such a system for quantum simulations and for quantum computing, we need to detect and to manipulate individual atoms on their lattice sites, while maintaining a sufficiently tight spacing to allow for a nearest neighbor coupling through tunneling.

We demonstrate in situ-imaging of ultracold ^{87}Rb atoms in an optical lattice ($\lambda = 1064$ nm) using fluorescence detection with a high resolution optical imaging system ($NA = 0.7$, ~ 700 nm resolution). We observe the transition from a Bose-Einstein condensate to a Mott insulator (MI). Due to inelastic collisions, atoms from doubly occupied sites are immediately expelled from the trap during illumination with the optical molasses. This allows us to clearly see the MI shell structure, since evenly occupied sites are detected as empty sites. In the MI regime, we directly observe number squeezing and determine the temperature of the system by counting the number of particle-hole pairs.

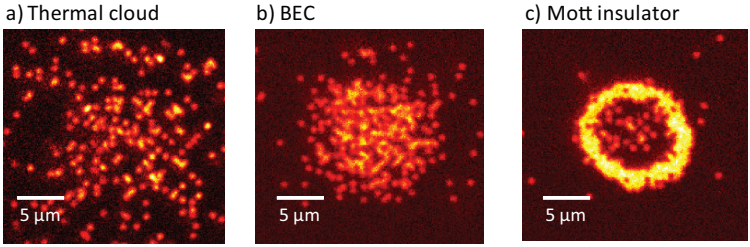

Figure 1: *Recent fluorescence pictures from ultracold atoms, held in two adjacent slices of a 3D optical lattice. Atoms are illuminated and simultaneously sub-Doppler cooled with an optical molasses. We typically detect a few hundred photons per atom in 800 ms.*

Ultracold fermions on a honeycomb lattice

K.L. Lee[1,2,3], R. Han[1], B.G.- Englert[1,5], K. Bouadim[6], G.G. Batrouni[4,1], F. Hébert[4], R.T. Scalettar[7], C. Miniatura[4,1,5] B. Grémaud[3,1,5]

[1]*Centre for Quantum Technologies, NUS, Singapore*
[2]*NUS Graduate School for Integrative Sciences and Engineering, NUS, Singapore*
[3]*Laboratoire Kastler-Brossel, UPMC-Paris 6, ENS, CNRS, France*
[4]*INLN, Université de Nice-Sophia Antipolis, CNRS, France*
[5]*Department of Physics, NUS, Singapore*
[6]*Department of Physics, Ohio State University, Ohio, USA*
[7]*Physics Department, University of California, Davis, California, USA*

Some important features of the graphene physics can be reproduced by loading ultracold fermionic atoms in a two-dimensional optical lattice with honeycomb symmetry and we address here its experimental feasibility. We analyze in great detail the optical lattice generated by the coherent superposition of three coplanar running laser waves with respective angles $2\pi/3$. The corresponding band structure displays Dirac cones located at the corners of the Brillouin zone and close to half-filling this system is well described by massless Dirac fermions. We characterize their properties by accurately deriving the nearest-neighbor hopping parameter t as a function of the optical lattice parameters. Our semiclassical instanton method proves in excellent agreement with an exact numerical diagonalization of the full Hamilton operator in the tight-binding regime. We conclude that the temperature range needed to access the Dirac fermions regime is within experimental reach. We also analyze imperfections in the laser configuration as they lead to optical lattice distortions which affect the Dirac fermions. We show that the Dirac cones do survive up to some critical intensity or angle mismatches which are easily controlled in actual experiments. In the tight-binding regime, we predict, and numerically confirm, that these critical mismatches are inversely proportional to the square root of the optical potential strength. We also briefly discuss the interesting possibility of fine tuning the mass of the Dirac fermions by controlling the laser phase in an optical lattice generated by the incoherent superposition of three coplanar independent standing waves with respective angles $2\pi/3$.

To address the question of interacting fermions, we study the attractive fermionic Hubbard model on a honeycomb lattice using determinantal quantum Monte Carlo simulations. By increasing the interaction strength U (relative to the hopping parameter t) at half filling and zero temperature, the system undergoes a quantum phase transition at $5.0 < U_c/t < 5.1$ from a semimetal to a phase displaying simultaneously superfluid behavior and density order. Doping away from half filling, and increasing the interaction strength at finite but low temperature T, the system always appears to be a superfluid exhibiting a crossover between a BCS and a molecular regime. These different regimes are analyzed by studying the spectral function. The formation of pairs and the emergence of phase coherence throughout the sample are studied as U is increased and T is lowered.

Multifractality in the kicked rotator

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[2]*Departamento de Física, Lab. TANDAR, Comisión Nacional de Energía Atómica, Av. del Libertador 8250, C1429BNP Buenos Aires, Argentina*
[3]*Université Paris-Sud, LPTMS, UMR8626, Bât. 100, 91405 Orsay, France*
CNRS, LPTMS, UMR8626, Bât. 100, Université Paris-Sud, 91405 Orsay, France
[4]*Université de Toulouse, UPS, Laboratoire de Physique Théorique (IRSAMC), F-31062 Toulouse, France*
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Multifractal wave functions appear in a wide range of systems intermediate between integrable and chaotic systems. Their properties can be described by a set of multifractal dimensions that can be extracted from the non-trivial scaling of their moments[1]. In this communication, we present our results on the multifractality of wave functions at the Anderson transition. More particularly, we focus on the kicked rotator model with three incommensurate frequencies[2], which has been shown to exhibit a localization-delocalization transition with increasing kicking strength. This transition could even be probed experimentally in the atom-optics realization of the system[3]. We also consider a one-parameter family of quantum maps displaying the whole range of intermediate spectral statistics and relate the multifractal dimensions to these spectral properties[4].

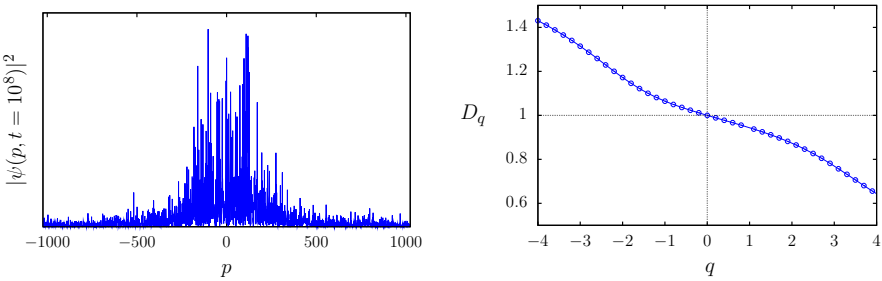

Figure 1: *(left) Multifractal wavefunction of the kicked rotator after* $t = 10^8$ *kicks. (right) Multifractal dimensions* D_q *extracted from 500 realizations.*

[1]F. Evers and A. D. Mirlin, Rev. Mod. Phys. **80**, 1355 (2008).
[2]G. Casati, I. Guarneri and D. L. Shepelyansky, Phys. Rev. Lett. **62**, 345 (1989).
[3]J. Chabé et al., Phys. Rev. Lett. 101, 255702 (2008).
[4]J. Martin, O. Giraud and B. Georgeot, Phys. Rev. E 77, 035201(R) (2008).

Mott Transition of Bose-Fermi Mixtures in Optical Lattices Induced by Attractive Interactions

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Bose-Fermi Hubbard model has successfully described mixtures of boson and fermion atoms confined on optical lattices in various situations. However remarkable phenomena, which cannot be explained with this model, have been observed in recent experiments of the Bose-Fermi mixtures in optical lattices[1] [2] [3]. With repulsive Bose-Bose interactions and attractive Bose-Fermi interactions, the boson component atoms lost their coherence and seemed to form a Mott state as the fermion component atoms were introduced among them.

Lühmann et al., [4] discussed that this could be attributed to the boson's self-trapping effect caused by the attractive boson-fermion interactions. The more bosons reside in each well of the optical lattice potential, the more squeezed the wave function of the fermions inside the well is and the deeper the effective lattice potential for both the bosons and the fermions becomes.

In Ref. [4], the authors applied the exact diagonalization technique to the effective Hamiltonian to derive the contribution of the self-trapping effect. We consider, on the other hand, that the original Hamiltonian of the interacting bosons and fermions in the periodic potential can have another decoherence effect. In order to show the decoherence effect of the original Hamiltonian, we analyzed higher-order effects of the Bose-Fermi interactions in the optical lattice potential and tried to analytically extract modified bosonic and fermionic hopping terms in the tight-binding approximation. With this modification that arises only in the mixture systems we can explain the decoherence of the bosons in the presence of the fermions.

We introduced a modified Bose-Fermi Hubbard model using the hopping terms that could change by the number of the bosons and the fermions. For direct observation of the physical properties of the modified Hubbard model, we performed quantum Monte Carlo simulations and studied the fermion-induced Mott transition of the bosonic component atoms. We found that the superfluidity in uniform systems (or the visibility of bosonic momentum distribution in trapped systems) changed drastically with the total number of the bosons and the fermions, suggesting the formation of a Mott state (or a local Mott state in the trapped systems).

[1] K. Günter et al., Phys. Rev. Lett. **96**, 180402 (2006).
[2] S. Ospelkaus et al., Phys. Rev. Lett. **96**, 180403 (2006).
[3] Th. Best et al., Phys. Rev. Lett. **102**, 030408 (2009).
[4] D.-S. Lühmann et al., Phys. Rev. Lett. **101** 050402 (2008).

Holographic sub-micron atom traps

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Single neutral atoms trapped in optical dipole traps present a feasible approach to construct a quantum computer, as well as providing a versatile platform for direct investigation of individual quantum events. The capability to manipulate and rearrange the position of individual atoms in the optical potentials is crucial to the above fields, and has been the subject of intense research[1] [2] [3].

We use a Spatial Light Modulator (SLM) to create such dynamic optical dipole traps for the use of trapping and manipulating single atoms. We create a hologram to impart phase and amplitude information on an incident laser beam and by focusing with a high numerical aperture lens (NA=0.55), we can create a 1D lattice of atom trapping potentials with sub-micron well separation. The intensity flicker (a product of the SLM's refresh rate at 60Hz) is compensated with a simple feedback circuit and an acousto-optic modulator (AOM). By dynamically changing our hologram we can change the position of the lattice potentials, thereby creating a single beam scheme for moving and sorting individual atoms.

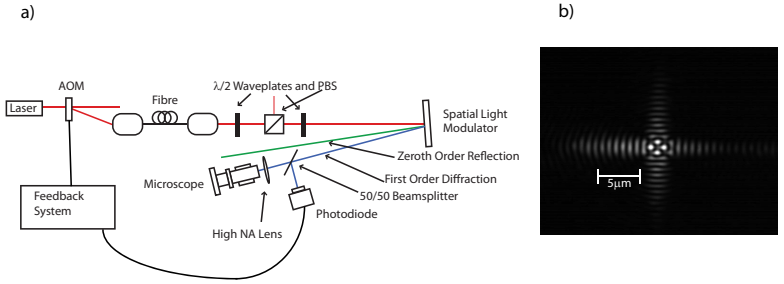

Figure 1: *a) Setup for using an SLM to create dynamic dipole traps and a system for imaging them. b) Image of two lattice potentials with sub-micron well separation ($0.78\mu m$), capable of manipulating and rearranging single atoms.*

[1] Y. Miroshnychenko, W. Alt, I. Dotsenko, L. Förster, M. Khudaverdyan, D. Schrader, A. Rauschenbeutel and D. Meschede, *Nature* **442** 151 (2006).

[2] J. Beugnon, C. Tuchendler, H. Marion, A. Gäetan, Y. Miroshnychenko, Y. R. P. Sortais, A. M. Lance, M. P. A. Jones, G. Messin, A. Browaeys and P. Grangier, *Nature Physics* **3** 696 (2007).

[3] S. Bergamini, B. Darquié, M. Jones, L. Jacubowiez, A. Browaeys and P. Grangier, *J. Opt. Soc. Am. B* **21**, 1889 (2004).

Phase diagram of ultracold Bose-Fermi mixtures in optical lattices

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We present analytic results for the phase diagram of Bose-Fermi mixtures in optical lattices. First restricting to the case of infinite fermionic mobility, we show the emergence of charge density wave phases (CDW) in one dimension resulting from fermion mediated effective density-density interactions between bosons. Using an effective Hamiltonian for the description of the bosons, coexistance phases between Mott insulators (MI) and CDW are seen, uniquely characterized by a negative compressibility and in full agreement to numerical results (see left figure). Secondly we study the effect of higher Bloch bands and interaction-induced nonlinear tunneling contributions. We describe the Bose-Fermi mixture by an effective single-band Hamiltonian where higher bands are incorporated by means of virtual transitions. The renormalized bosonic hopping and interaction amplitudes are analyzed with respect to the shift of the Mott insulator to superfluid (SF) transition. The one-dimensional model qualitatively agrees with the experimentally observed shift of the MI to SF transition for both repulsive *and* attractive interactions (see right figure).

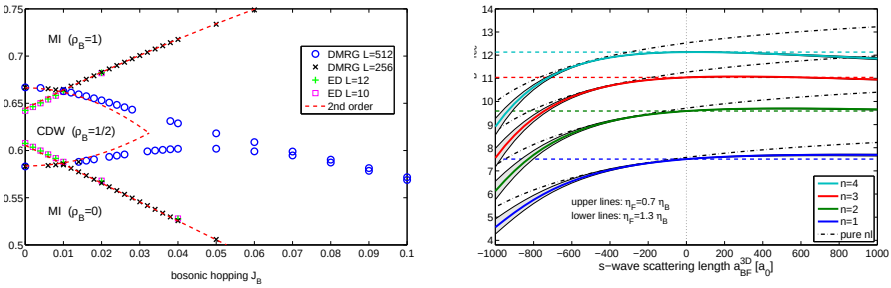

Figure: *Left: Phase diagram of the Bose-Fermi-Hubbard model in the limit of fast fermions. The coexistance phase with negative compressibility is seen in the overlap-regions of the MI and the CDW for small hopping. Dashed lines are analytic results, data points are numerical results from DMRG. Right: Shift of the MI-SF transition point with varying boson-fermion interaction calculated by inclusion of nonlinear and higher band effects. Shown are the results for the first four Mott-lobes calculated using non-approximated Wannier functions. Also shown is the effect of a mismatch of the bosonic (η_B) and fermionic (η_F) optical lattice strength.*

Quantum phase transitions in disordered optical lattices - a local mean-field approach

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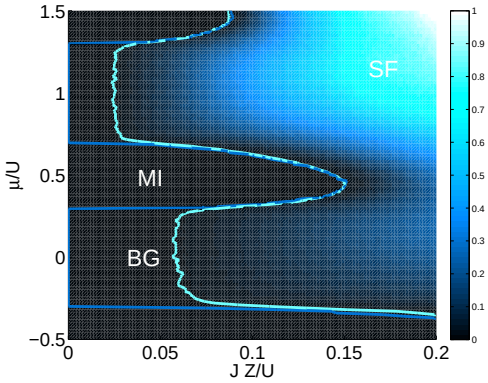
The Bose-Hubbard model represents an accurate theoretical description to study Bose-Einstein condensates in diverse kinds of optical lattices and the influence of disorder in these systems, which became a wide field of research. Especially the phase transitions in dependence of the system parameters constitute an interesting branch of study[1].
We focus on the properties of a Bose-Einstein condensate in an optical lattice with an equally distributed disorder in the on-site energy[2]. By the definition of the so called superfluid order parameter, which must be determined selfconsistantly, the Hamiltonian can be decomposed in a sum of on-site operators. This on-site Hamiltonian forms the starting point of our investigations, in order to observe the competing phases. They can be identified in dependence of the system parametes, analyzing the superfluid order parameter ψ and the compressibility κ. The insulating phase is confined to lobe-shaped regions in parameter space, the so called Mott lobes, and is surrounded by the superfluid phase. In the presence of disorder the Bose glass phase, which inherits features from both of them, appears in between. Our investigations in local mean-field theory give us a tool to explore the phase diagram in a large parameter range and for various geometries.



[1] M. P. A. Fisher, P. B. Weichman, G. Grinstein and D. S. Fisher, Phys. Rev. B **40**, 546 - 570 (1989)
[2] J. Kisker, H. Rieger, Phys. Rev. B **55**, 11981 (1997)

Excitation Spectrum of a Bose-Bose mixture in an Optical Lattice

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Systems of ultracold Bosonic atoms in an optical lattice have attracted attention to study strongly correlated quantum matter. One of the most interesting phenomena exhibited by ultracold Bosonic atoms in an optical lattice is superfluid (SF) to Mott insulator (MI) phase transition, as experimentally observed[1]. The properties of this system can be well captured by Bose-Hubbard model.

Adding the second atomic species, the system can exhibit rich quantum phases. Theoretical studies predict the existence of supersolid, pair superfluid and counterblow superfluid (CFSF) phases,inaddition to the ordinary SF phaseaand MI Phase. [2]. Recently, some experimental groups experimentally realized two-component $^{87}Rb^3$ and ^{87}Rb-$^{41}K^4$ mixtures trapped in an optical lattice. However, the predicted quantum phases have not been found experimentally so far.

We study the properties of a Bose-Bose mixture in an optical lattice at zero temperature by using Bose-Hubbard model for Bose-Bose mixtures. Especially, we consider the case of repulsive inter-species interaction. First, we obtain the ground-state phase diagram using the Gutzwiller mean-field approach. We determine the phase boundaries between different phases, such as MI phase, SF phase and CFSF phase. Second, we use the dynamical Gutzwiller approach to calculate excitation spectrum to identify the quantum phases. We derive the expression for Bogoliubov equations, and calculate the excitation spectrum in different phases.

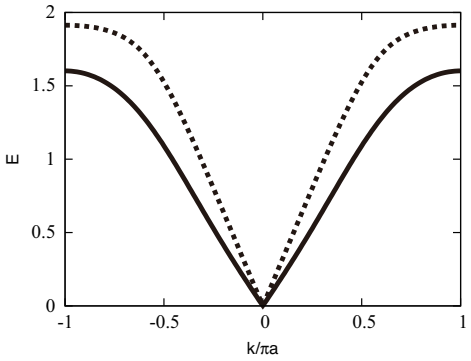

Figure 1: *Excitation spectrum in the SF phase.*

[1] M. Greiner, *et al., Nature* **415**, *39 (2002).*
[2] A. Kuklov, *et al., Phys. Rev. Lett.* **92**, *050402 (2004).*
[3] A. Widera, *et al., Phys. Rev. Lett.* **100**, *140401 (2008).*
[4] J. Catani, *et al., Phys. Rev. A* **77**, *011603(R) (2008).*

Phase transitions and intrinsic decoherence in a Bose fluid confined in a double well potential.

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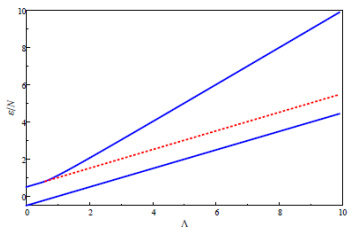
The system under consideration is a quantum Bose fluid confined in a double well potential in one dimension. First, study the delocalized to self-trapping transition as function of the energy in the closed system and the interactions among the particles in the full quantum approach, such transition is followed by monitoring one- and two-body properties in the energy eigenstates[1]. The evolution in time of the same observables in a set of coherent states allow us to show that the N-particle Bose fluid reach stationary states, whose expectation values turn out to coincide with those in the eigenestates. This stationarity property is in severe contrast with the results obtained using mean-field analysis. Such stationary or collapsed states alternate with recurrent revivals. Then, we show that the time spent in the stationary state increases with the number of particles, relatively to the time during the revivals. We further characterize the intrinsinc decoherence both, by the vanishing of the off-diagonal matrix elements of the one-body reduced density matrix, in what one may call the preferred basis, and by the value of its associated von Neumman entropy[2].



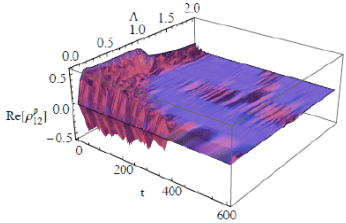


Figure : *1. Phase diagram ε/N vs Λ. The allowed states are those within the blue lines, $\varepsilon_0(\Lambda)$ and $\varepsilon_N(\Lambda)$. The red line signals the transition. 2. Real component of the matrix element ρ^p_{12} as a function of t and Λ in its own preferred basis. Calculations were performed using $N = 10^3$.*

[1]S.F. Caballero-Benítez, V. Romero-Rochín and R. P., J. Phys. B: At.. Mol. Opt. Phys., **43** 115301 (2010).
[2]S.F. Caballero-Benítez, V. Romero-Rochín and R. P., J. Phys. B: At.. Mol. Opt. Phys., **43** 095301 (2010).

Creation of Arbitrary Spectra with an Electro-Optical Modulator

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We use a waveguide-based Mach-Zehnder-type electro-optical phase modulator, in conjunction with an arbitrary waveform generator, to produce an arbitrary pattern of sidebands. A linear voltage ramp applied to the modulator changes the optical phase linearly in time. The resulting frequency shift, equal to the time derivative of the phase, yields a single sideband. This is the principle behind serrodyne modulation[1,2]. If instead, a sequence of such ramps with differing slopes is repeatedly applied, a set of sidebands is generated. The frequency offset of a given sideband from the carrier is determined by the slope of the corresponding ramp. An example of such a generated spectrum is shown in Fig. 1. The time and frequency resolutions are restricted by Fourier considerations. There are also limitations due to the maximum phase change achievable with the modulator and the finite speed of the arbitrary waveform generator. Such multi-line spectra, with sideband spacings in the 100 MHz range, may find use in optical pumping and efficient excitation in multi-level systems. For example, recent work on optical cycling in molecules[3] required four frequencies to prevent ground-state hyperfine pumping. This work is supported by the U.S. Department of Energy.

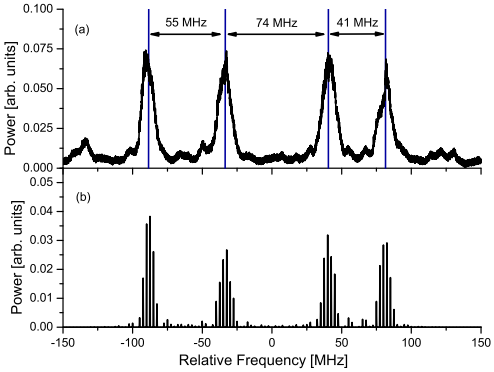

Figure 1: *(a) Measured 4-line spectrum produced by a sequence of voltage ramps of various slopes applied to the phase modulator. The frequency origin corresponds to the carrier. (b) Predicted spectrum based on the Fourier transform of the waveform applied to the modulator.*

[1] R. Houtz, et al., Optics Express **17**, 21 (2009).
[2] D.M.S. Johnson, et al., Optics Letters **35**, 5 (2010).
[3] E.S. Shuman, et al., Phys. Rev. Lett. **103**, 223001 (2009).

Archimedean Solids' Symmetry Operations with Clifford Algebra

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

Electron impact collision strengths in Dy XXXIX

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[2]*Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences*

We report here the energy levels, multipole (E1, M1, E2, and M2) transition rates, and electron impact collision strengths for Dy XXXIX. The data refer to 107 fine-structure levels belonging to the configurations $(1s^2 2s^2 2p^6)3s^2 3p^6 3d^{10}$, $3s^2 3p^6 3d^9 4l$,$3s^2 3p^5 3d^{10} 4l$, and $3s3p^6 3d^{10} 4l$ $(l = s, p, d, f)$. The collision strengths are calculated with a twenty-collision-energy grid in terms of the energy of the scattered electron between 51.5 and 7205 eV by using distorted-wave approximation. Effective collision strengths are obtained at seven electron temperatures: T_e (eV)=10, 100, 300, 500, and 800 by integrating the collision strengths over a Maxwellian electron distribution.[1, 2]

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[2]The author gratefully acknowledges the support of the International Union of Pure and Applied Physics

Polarization effects in optical lattice clocks

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Optical lattices are the integral components of time frequency standards based on transitions in cooled trapped neutral atoms. Particularly, the strictly forbidden 1S0-3P0 transition in even isotopes of alkaline-earth-like atoms (Sr, Yb, Mg, Ca, Zn, Cd) was intensively investigated during the last few years in purport to be used as ultrastable quantum oscillator with quality factor $Q > 10^{17}$. Designing of atomic clocks with this high level of stability requires particular consideration of all detrimental factors, affecting it. Particularly, the disturbance of clock levels by the lattice field can not be neglected. In linear dipole approximation the clock frequency shift can be cancelled by use of "magic" wave length, at which the dipole polarizabilities of upper and lower clock levels coincide. Recently there were considered [1] the special configurations of 2D 3D lattices allowing to exclude the uncertainties due to the multipole M1 E2 effects. There were also presented [2] the prospects for optical clocks with blue-detuned lattices at which the contribution of nonlinear effects can be well reduced in comparison with case of red-detuned lattices. Here we investigated the nonlinear and anharmonic effects on optical lattice clocks in dependence on polarization of trapping field. The hyperpolarizabilities of $^1S_0$, $^3P_0$ states in linearly and circularly polarized electromagnetic fields were calculated for series of alkaline-earth-like atoms at corresponding values of "blue" and "red" "magic" wave lengths. The calculated values are sufficient to determine the nonlinear energy Stark shifts of considering states in field with arbitrary polarization. The possibility to induce the strictly forbidden $^1S_0 -^3 P_0$ transition in even isotopes of alkaline-earth-like atoms by use of specially configured 2D,3D lattices as well as by use of additional to the lattice "magic" running wave with non zero degree of circular polarization is considered. The ways to reduce the contribution of nonlinear and anharmonic effects to the clock frequency shift by manipulating the polarizations of trapping (mixing), scanning fields (with account of symmetry features of states with zero total angular momentum in electromagnetic field) are discussed.

1 H.Katory et.al. PRL 103, 153004 (2009)

2 M. Takamoto et. al. PRL 102, 063002 (2009).

Frequency comb spectroscopy of rubidium Rydberg states using purely optical detection

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Recently we have used a three-step laser excitation scheme to make absolute frequency measurements of highly excited $n\mathrm{F}_{7/2}$ Rydberg states in ^{85}Rb for principal quantum numbers n=33-100 [1]. This work demonstrated the first absolute measurements of rubidium Rydberg levels using a purely optical detection scheme in an ordinary vapour cell. It also gave the first absolute measurements for this range of nF states. The setup used is much simpler to maintain than a conventional field ionization apparatus and Doppler free Rydberg signals can be detected via purely optical means with an ordinary photodiode. We also found that the measured levels had a very high frequency stability and, like other groups, we found that they were especially robust to applied DC electric fields. The apparatus allowed measurements of the states to an accuracy of 8.0MHz with the aid of a wavemeter which was calibrated against a GPS disciplined self-referenced optical frequency comb.

We have now constructed a new apparatus which removes the need of the wavemeter, and allows us to continue with the measurements with an almost 80$\times$ improvement in absolute accuracy ($\pm$100kHz). In order to do this we have developed a system which allows all three laser steps, at 780nm, 776nm and 1260nm respectively, to be stabilised to the same frequency comb simultaneously at different lines. This is possible due to all three transitions being in the infra-red. The setup allows independent frequency control of the third step laser across a 45MHz range with kHz resolution, whilst the first two steps remain fixed at the respective transition frequencies. Preliminary results show remarkable agreement with results from microwave spectroscopy and also with a comparable accuracy. These new numbers give a value for the ionisation energy of ^{85}Rb to a part in 10^{10}. We now hope to use the system to carry out precision measurements of Rydberg-Rydberg interactions inside the cell. We are also in the process of adding a fourth (microwave) field to the excitation scheme to study nG Rydberg states. These states are conventionally hard to study due to their high sensitivity to electric fields, they are however ideally suited to this setup.

[1]L. A. M Johnson *et al*, arXiv:1002.3066v1 [quant-ph] (2010). To be published in New. J. Phys.

Proposed detection of the variance in m_p/m_e via the vibrational transition frequencies of cold XH^+ molecular ions (X = ^{40}Ca, ^{24}Mg, ^{64}Zn, or ^{114}Cd)

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The precise measurement of molecular vibrational transition frequency is useful for the detection of the variance in the proton-to-electron mass ratio. The ratio of the variances between the fine structure constant (measured from the comparison between different atomic transitions) and the proton-to electron mass ratio gives useful information to develop the Grand Unification Theory. [1]

This presentation gives a proposal to measure the $(^1\Sigma, v = 0, J = 0, F = 1/2, M = \pm 1/2) \rightarrow (^1\Sigma, v = 1, J = 0, F = 1/2, M = \pm 1/2)$ transition frequencies of XH^+ molecular ions (X: even isotopes of Mg, Ca, Zn, or Cd). The measuremnt procedure is shown below. [2]

1. Trap one X^+ and one Y^+ ions (Y^+ must have a meta-stable state) in a linear trapping system. The temperature of the surrounding circumstance should be cooled by Liq. He, so that XH^+ molecular ion is localized in the $(^1\Sigma, v = 0, J = 0, F = 1/2)$ state

2. Production of XH^+ molecular ion via the chemical reaction: $X^+ + H_2 \rightarrow XH^+ + H$ (X^+ should be in the P state)

3. Sympathetic cooling with laser cooled Y^+ ion

4. Measurement of the XH^+ vibrational transition frequency using the quantum information treatment with Y^+ ion

The frequency shift is actually dominated by the Stark effect induced by the probe laser. With the saturation power density of the probe laser, the Stark shift is of the order of 10^{-14}. This shift can be eliminated from the dependence of the transition frequency on the power density of the probe laser.

The vibrational transition frequency of cold XH^+ molecular ions can be measured with the uncertainty lower than 10^{-15}.

[1] X. Calmet and H. Fritzsch, Euro. Phys. J. C 24, 639, (2002).
[2] M. Kajita and Y. Moriwaki, J. Phys. B 42, 154022, (2009).

A ring of ions in a linear octupole trap for optical metrology

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[2]*National Institute of Information and Communications Technology, Koganei, Tokyo*

The quadrupole linear radiofrequency (RF) trap is a widespread tool for many fundamental physics experiments where a small number of cold ions are required, like for quantum computing experiments. Compared to this trap, higher order linear traps present the interesting feature to generate an almost flat potential well, which allows one to trap a larger number of ions with a reduced RF-driven motion. This advantage is exploited in microwave frequency standards[1], working with large clouds of trapped ions ($> 10^6$ ions) cooled to room temperature by buffer gas cooling, which ensure a good short-term stability (characterized by an Allan deviation $\sigma_y(\tau) < 10^{-13}/\sqrt{\tau}$) and an excellent long-term stability ($\sigma_y(\tau) < 10^{-16}$ per day).

During the last few years, laser cooling and phase transition of ion clouds[2] have been observed in a linear octupole trap. These experimental and numerical results, as well as the study of the stationary structures and phase transitions of ions in an isotropic three-dimensional octupole trap[3] show that a cold ion cloud can be described as a hollow core system, resulting from the balance between the Coulomb repulsion and a trapping potential very steep at the border. When the number of trapped ions is reduced to the order of 100 or less, simulations show that for certain trapping parameters, the tube formed by the ions reduces to a ring crystal, centered on the symmetry axis.

We propose[4] to use laser-cooled ions trapped in a linear multipole RF trap and organized in a ring structure as a basis for an optical clock. Compared to single ion clock, the aim is to propose a tradeoff between a loss in precision and a gain in short-term stability, offered by the interrogation of several ions at the same time. Compared to a chain of ions in a linear quadrupole trap, this ring configuration ensures that every ion sees the same laser intensity and that the motion along the trap axis is characterized by a single oscillation frequency. Furthermore, the trapping parameters can be chosen to constrain the radial size of the ring, independent of the number of trapped ions, to first order (if this number obeys some stability conditions).

In this presentation, we first describe the features concerning the trapping and cooling of the ion sample, relevant for an optical clock of this kind. We then present the scaling laws and numerical values of the systematic shifts related to the ring configuration to quantify the expected performances of such a clock.

[1] J. Prestage, R. Tjoelker, and L. Maleki, Frequency Measurement and Control: Advanced Techniques and Future Trends (Springer, Berlin, 2001), p. 195.

[2] K. Okada, K. Yasuda, T. Takayanagi, M. Wada, H. A. Schuessler, and S. Ohtani, Phys. Rev. A **75**, 033409 (2007), K. Okada, T. Takayanagi, M. Wada, S. Ohtani, and H. A. Schuessler, Phys. Rev. A **80**, 043405 (2009).

[3] F. Calvo, C. Champenois, and E. Yurtsever, Phys. Rev. A **80**, 063401 (2009).

[4] C. Champenois, M. Marciante, J. Pedregosa-Gutierrez, M. Houssin, M. Knoop and M. Kajita, Phys. Rev. A **81**, 043410 (2010).

Atom Interferometry Experiments in Fundamental Physics

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Light-pulse atom interferometers have already been used to measure gravity, the fine structure constant, gravity gradients, Newtons gravitational constant, and gravitational redshift with high precision and accuracy. Recent developments like large-momentum transfer (LMT) beam splitters for matter waves, e.g. using a combination of Bloch oscillations and Bragg diffraction, increase the space-time area enclosed between the interferometer arms[1]. This promises to boost the sensitivity of atom interferometer by several orders of magnitude. Furthermore, the common mode noise of interferometers can be removed by running a pair of conjugated interferometers simultaneously[2]. Here, we report our recent progress of atom interferometer experiments.

[1] H. Müller, S.-w. Chiow, S. Herrmann, and S. Chu, Phys. Rev. Lett. **102,** 240403 (2009).
[2] S.-w. Chiow, S. Herrmann, S. Chu, and Holger Müller, Phys. Rev. Lett. **103,** 050402 (2009).

Precision Measurement of the 1S – 2S Transition in Atomic Hydrogen and Deuterium

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We have measured the hydrogen-deuterium isotope shift via two photon spectroscopy of the $1S-2S$ transition. We obtain 670 994 334 606(15) Hz which is a 10 times improvement over the previous best measurement [A. Huber *et al.*, Phys. Rev. Lett. **80**, 468 (1998)] confirming its frequency value. Using this result to calculate the difference of the mean square charge radii of deuterium and hydrogen we obtain $\langle r^2\rangle_d - \langle r^2\rangle_p = 3.82007(65)\,\mathrm{fm}^2$, a more than twofold improvement compared to the former value.

Also, we hope to report on a new measurement of the absolute frequency of the $1S-2S$ transition in atomic hydrogen.

Cavity Detection of Atom Laser Squeezing

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We aim to develop high quantum efficiency (QE) detectors for single, neutral, ground state atoms, capable of measuring squeezing in an atom laser beam. Squeezing has been measured in cold atom ensembles[1,2], but not in a continuous source such as an atom laser, and the process of detection of such a phenomenon will be a significant consideration.

Optical cavities have already been used to detect single atoms, but the focus of previous work has been on strongly coupled cavity QED experiments, rather than on QE [3,4,5]. To measure squeezing it is necessary to use detectors with high QE and low noise. In previous investigations we found that relatively low finesse cavities ($F \sim 10^4$) can provide detection signal-to-noise ratios that are comparable to cavities with finesse 10 times larger[6].

Here we extend our study to investigations of detector noise and efficiency. We consider the signal processing that determines which events correspond to atom transits, rather than detector dark noise, and include atomic motion within the cavity mode. In a red-detuned laser, the dipole force very effectively channels atoms into the antinodes of the cavity standing wave pattern. This reduces the range in signal strengths, allowing a discriminating threshold to be chosen that clearly distinguishes between real transits and dark-noise, thus enabling high QE to coincide with low noise. These parameters in turn result in a detector that will be able to measure squeezing with a noise-floor clearance of more than 20dB.

[1] M.F. Riedel, P. Böhi, Y. Li, T.W.Hänsch, A. Sinatra, P. Treutlein, "Atom-chip-based generation of entanglement for quantum metrology" Nature 464, 1170 (2010)

[2] C. Gross, T. Zibold, E. Nicklas, J. Estéve, M. K. Oberthaler, "Nonlinear atom interferometer surpasses classical precision limit", Nature 464, 1165 (2010)

[3] H.J. Kimble, "Strong Interactions of Single Atoms and Photons in Cavity QED", Phys. Scripta 76, 127 (1998)

[4] P. Münstermann, T. Fischer, P.W.H. Pinkse, G Rempe, "Single slow atoms from an atomic fountain observed in a high-finesse optical cavity", Opt. Comm. 159, 63 (1999)

[5] A. Öttl, S. Ritter, M. Khl, T. Esslinger "Hybrid apparatus for Bose-Einstein condensation and cavity quantum electrodynamics: Single atom detection in quantum degenerate gases", Rev. Sci. Instrum. 77, 063118 (2006)

[6] R. Poldy, B.C. Buchler and J.D. Close, "Single-atom detection with optical cavities", Phys. Rev. A 78, 013640 (2008)

Effect of atomic electrons on the ^{229m}Th – ^{229g}Th nuclear transition in ^{229}Th^{3+} and ^{229}Th^{+}.

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The ^{229}Th nucleus is unique in the sense that the energy splitting of the ground state doublet is only several eV. Though prediction of the existence of such a low-lying level was made more than 30 years ago the definite value of energy of the isomeric state ^{229m}Th is not known so far. As to the lifetime of the ^{229m}Th, measurements performed by different experimental groups led to different values. The results differ from each other by several orders of magnitude, changing from a few minutes to many hours.

Special interest in the nuclear transition from the isomeric state ^{229m}Th to the ground state ^{229g}Th is motivated by a possibility to build a superprecise nuclear clock[1] and very high sensitivity to the effects of possible temporal variation of the fundamental constants, including the fine structure constant α, strong interaction, and quark mass[2].

Laser cooling of the ^{232}Th^{3+} ion was recently reported[3]. This was the first time when a multiply charged ion has been laser cooled. As a next step this experimental group plans to investigate the nuclear transition between the isomeric and the ground state in a trapped, cold ^{229}Th^{3+} ion.

Motivated by this experimental progress we have considered the ^{229}Th^{3+} ion and calculated the transition probability of the ^{229}Th nucleus from its lowest-energy isomeric state ^{229m}Th to the ground state ^{229g}Th due to the electronic bridge process. Based on the recent experimental result we assumed the energy difference between the isomeric and the ground nuclear states to be equal to 7.6 eV. We have calculated the ratios of the electronic bridge process probability ($\Gamma_{\rm EB}$) to the probability of the nuclear radiative transition (Γ_N) for the electronic $5f_{5/2} \to 6d_{3/2}, 6d_{5/2}, 7s$ and the $7s \to 7p_{1/2}, 7p_{3/2}$ transitions and found $\Gamma_{\rm EB}/\Gamma_N \sim 0.01-0.1$ for the former and $\Gamma_{\rm EB}/\Gamma_N \sim 20$ for the latter[4].

We have also studied the effect of atomic electrons on the nuclear transition from the isomeric ^{229m}Th state to the ground ^{229g}Th state in ^{229}Th^{+} due to the electronic bridge process. Since the exact value of the nuclear transition frequency is unknown, we have developed a formalism that can be used for any nuclear transition frequency. We have calculated positions of several high-lying even-parity states which are not presented in experimental atomic spectra databases. We have found their energy levels and g factors[5].

[1] E. Peik and C. Tamm, Europhys. Lett. **61**, 181 (2003)
[2] V. V. Flambaum, Phys. Rev. Lett. **97**, 092502 (2006)
[3] C. J. Campbell, A. V. Steele, L. R. Churchill *et al.*, Phys. Rev. Lett. **102**, 233004 (2009)
[4] S. G. Porsev and V. V. Flambaum, Phys. Rev. A **81**, 032504 (2010)
[5] S. G. Porsev and V. V. Flambaum, Phys. Rev. A **81**, 042516 (2010)

Constraining the Evolution of the Fundamental Constants with a Solid-State Optical Frequency Reference Based on the ^{229}Th Nucleus

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The technological impact of atomic clocks has been profound, ranging from the successful implementation of global positioning systems and cellular telephones to the synchronization of modern-day electrical power grids. Improved clocks, based on optical frequency standards are likely to have real-world utility at an even greater level. Furthermore, high precision clocks have provided a means to probe fundamental issues in physics. For example, atomic clocks have provided some of the most stringent tests of General Relativity[1] and the variability of the fundamental constants[2]. Because of these motivations, there is presently enormous effort towards building next-generation atomic clocks. It appears univerally recognized that the most promising route to improved clocks uses reference oscillators based on optical transitions. Indeed, several optical atomic clock experiments have already reported better stability than the primary U.S. Cesium standard[2,3].

We have recently described a novel optical frequency reference[4]. Based on a high-Q transition in the ^{229}Th nucleus, this "nuclear" clock architecture promises up to six orders of magnitude improvement in precision over next-generation optical clocks, while simultaneously reducing experimental complexity. This paradigm shift in optical frequency references is possible because, as indicated by recent data[5], the ^{229}Th transition has the lowest energy of any known nuclear excitation, making it amenable to study by laser spectroscopy. Furthermore, because nuclear energy levels are relatively insensitive to their environment, the complicated vacuum apparatus of current optical frequency refernces can be replaced by a single crystal doped with ^{229}Th atoms.

We present the effect of the solid-state environment on the nuclear transition, and show that it allows for the construction a solid-state optical frequency reference with higher precision than current clocks, as well as allowing a 2-3 order of magnitude improvement in the current best limits for the variability of several important fundamental constants. We also detail our plan to make the first precision measurement of the ^{229}Th transition.

[1]N. Ashby *et al.*, Phys. Rev. Lett., **98**, 070802 (2007).
[2]T. Rosenband *et al.*, Science, **319**, 1808 (2008).
[3]A.D. Ludlow *et al.*, Science, **319**, 1805 (2008)
[4]W.G. Rellergert *et al.*, Phys. Rev. Lett., **104**, 200802 (2010).
[5]B.R. Beck *et al.*, Phys. Rev. Lett., **98**, 142501 (2007).

Optical Trapping of Magnesium

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Magnesium is an interesting candidate element for a high performance neutral atom optical frequency standard. It offers low sensitivity to room temperature blackbody radiation, one of the largest uncertainty contributions in state-of-the-art lattice clocks with Strontium[1]. To perform high-resolution spectroscopy on the ${}^1S_0 \rightarrow {}^3P_0$ transition, it is necessary to confine the atoms to the Lamb-Dicke regime in an optical lattice at the magic wavelength. Magnesium is challenging because cooling in a MOT on the strong singlet transition is limited to the Doppler limit of 2 mK. Cooling on narrow lines, a standard technique to reach ultralow temperatures for other alkaline-earth atoms, is not promising for Mg because of a too narrow ${}^1S_0 \rightarrow {}^3P_1$ intercombination line (36 Hz).

As an additional cooling step, we implemented a second MOT on the triplet transition ${}^3P_2 \rightarrow {}^3D_3$. To load this trap, atoms are first cooled on the strong singlet transition and then optically transferred to the triplet system. With this second MOT as a source of cold atoms, we study the loading of an optical dipole trap at 1064 nm as a first step towards a lattice based frequency standard. For optimal loading of the trap, we operate all cooling stages, the dipole trap and the transfer to the triplet system at the same time. In the second MOT, atoms decay to the dark ${}^3P_0$ state and can be accumulated in the dipole trap. With this continuous loading scheme, we are able to trap more than 10^5 atoms at a temperature below 100 μK. At this point, the atom number in the trap is limited by inelastic collisions between ${}^3P_0$ atoms.

For a dipole trap at the wavelength 532 nm, we observe strong losses due to photoionization of the ${}^3D_3$ state. This process is also possible at the predicted magic wavelength of magnesium, so the loading scheme cannot directly be transferred to such a trap. However, atoms from the infrared trap can be transferred to a second optical trap at 532 nm. This technique can also be used for a high-performace optical frequency standard.

[1]Ludlow et al., Science, 314, 1430 (2008)

Towards Direct Frequency Comb Spectroscopy of Trapped Ions using Quantum Logic

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The variation of fundamental constants is an intriguing prediction of unifying theories beyond the standard model. Most experimental approaches to detect a variation of e.g. the fine-structure constant α are based on a comparison of spectral lines that depend differently on a change in α. Laboratory searches for a present-day variation compare the transition frequency of accurate optical clocks over the course of several years. Access to variations over astronomical time scales is provided by comparing quasar absorption lines with present-day laboratory spectra. The result of these astronomical investigations is highly disputed [1, 2]. The analysis of quasar absorption lines requires a more detailed knowledge of spectra and isotope shifts of a number of neutral atoms and ions than is currently available [3].

We describe a versatile spectroscopy system to investigate the spectra and isotope shifts of trapped metal ions relevant for quasar absorption spectroscopy. The broadband output of a stabilized and cesium-referenced optical frequency comb will be used for probing the spectroscopy transitions and repumping metastable states. The typically rather complex spectra of these ions renders laser cooling and state detection difficult. We plan to use magnesium as a "logic" ion to provide sympathetic cooling and detection for the spectroscopy ions. For this, magnesium is trapped simultaneously with the spectroscopy ions in a linear Paul trap. Raman sideband transitions on magnesium cool the ion crystal to the ground state of motion in the trap. Optical resonances between frequency comb and ions lead to an increase of scattered photons and via photon recoil to motional heating. This heating represents the spectroscopy signal which can be detected very efficiently on the magnesium ion using methods derived from quantum information processing with trapped ions. We will report on progress towards precision spectroscopy of calcium, titanium and iron ions using different spectroscopy approaches.

The combination of broad-band direct frequency spectroscopy and sympathetic cooling and detection via quantum logic opens the door for spectroscopy of previously inaccessible atomic and molecular ions for a variety of applications, including quasar absorption spectroscopy.

[1] M.T. Murphy *et al.*, Mon. Not. R. Astron. Soc. **345**, 609 (2003)
[2] R. Srianand *et al.*, Phys. Rev. Lett. **92**, 121302 (2004)
[3] J.C. Berengut, *et al.*, arXiv: physics/0408017v3 (2006)