Poster Session I

Monday, July 28
4:15 pm – 6:00 pm
Wilbur Cross Building, Reading Rooms

Atomic and Ionic Structure

Spectroscopy

Atomic Clocks

Atoms in External Fields

Optical Lattices

Quantum Information

Quantum Optics & Cavity QED

Multi-configuration Dirac-Fock Calculations for Atomic Structures of Ca^+

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The metastable $3d\,^2D_{3/2,5/2}$ states of Ca^+ are interesting in various experimental fields such as optical frequency standards[1], quantum information science[2], and astrophysics[3]. Ca^+ is also a challenging system for the calculations of atomic structure, due to the effects of d orbitals and strong core-valence correlation effects[4]. Recently, a lot of experimental[5,6] and theoretical[5,7] research works have been done for the lifetimes of $3d\,^2D_{3/2,5/2}$ states of Ca^+.

In this letter, we calculated the $3d\,^2D_{3/2,5/2}$ and $4p\,^2P_{1/2,3/2}$ energy levels of Ca^+, using multi-configuration Dirac-Fock (MCDF) method with the Breit interactions and quantum electrodynamics corrections. Based on multi-configuration self-consistent field (MCSCF) calculation strategies[8], we optimized a set of high-quality orbital basis. Owing to the feature of d orbital in Ca^+, the obitals with approximate equal effective quantum number $\nu = n - \mu$ are defined as a layer, e.g. $4s$, $3d$ and $4p$ constitute the $\nu = 2$ layer. In order to consider the core-valence correlation, the configurations created by single excitations respectively from core $3p^6$ and valence $4s^1$ are included. In order to consider the monopole, dipole and quadrupole excitation correlations uniformly, the $4f$ and $5g$ orbitals are included when optimizing the $\nu = 2$ layer. Then the obital basis is extended by single configuration optimization to $\nu = 7$ layer. The configurations created by single excitation from deeper core $3s^2$ are also included in the configuration interaction calculations. Finally, we obtained a uniform convergence for the energy levels. The percentage differences between our calculated energy levels and available experimental results are approximate 1% for $^2D_{3/2,5/2}$ and 0.1% for $^2P_{1/2,3/2}$.

It is anticipated that all of the E1, E2 and M1 radiation transition rates between the states of $^2S_{1/2}$, $^2D_{3/2,5/2}$ and $^2P_{1/2,3/2}$, as well as the lifetimes of $^2D_{3/2,5/2}$ and $^2P_{1/2,3/2}$ states, can be calculated in high precision based on the MCSCF calculation strategies presented in this letter.

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Isotope shift in the electron affinity of sulfur: observation and theory

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Photodetachment microscopy[1] was performed on a beam of S^- generated by a hot cathode discharge in a mixture of 98% Ar and 2% CS_2, with the sulfur isotopes in natural abundances. Isotope 34 was selected by a Wien velocity filter. Laser excitation was provided by a CW ring laser operating with the Rhodamine 590 dye. The laser wave-number was measured by an *Angström* WS-U lambdameter, with an accuracy better than 10^{-3} cm^{-1}. Subtracting the photoelectron energy found by analysing the electron interferogram from the photon energy, one can determine the electron affinity ${}^eA$. The result for ${}^eA({}^{34}S)$ is 16 752.978(10) cm^{-1}, to be compared to the previously measured[2] ${}^eA({}^{32}$S)=16 752.976(4) cm^{-1}. Technical correlations between the two measurements lets the isotope shift $\Delta_{exp} = {}^eA({}^{34}S) - {}^eA({}^{32}S)$ be a little more accurate than the more imprecise electron affinity. Numerically $\Delta_{exp} = +0.002(8)$ cm^{-1}, in wich the (2σ) error bars leave room for a normal or anomalous result.

Ab initio calculations of the isotope shift on the electron affinity from the infinite-mass systems S^-/S were carried out, adopting the multiconfiguration Hartree-Fock (MCHF) approach using the ATSP2K package[3]. Our model includes in a systematic way valence correlation, limiting the core to the n=2 shell. The one-electron orbitals are optimized using single- and double- multi-reference expansions. Configuration-iteraction (CI) calculations including up to $6{\cdot}10^5$ configuration state functions were performed in order to complete the convergence patterns of the S^- energy, resulting in a unextrapolated non-relativistic electron affinity of ${}^eA({}^\infty S) = 16\ 987(44)$cm^{-1}. The theoretical isotope shift value $\Delta_{theor} = {}^eA({}^{34}S) - {}^eA({}^{32}S) = -0.0022(2)$cm^{-1} is found to be rather small but definitely negative. The analysis of the various contributions reveals a very large specific mass shift that counterbalances the normal mass shift, while the positive field shift is smaller than the total mass contribution by one order of magnitude.

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On the Importance of an Electric Octupole Contribution to the Radiative Decay of Two Metastable States in Ar^+

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Most singly charged ions have metastable states that can live very long (lifetimes of the order of seconds or even more). Such levels usually decay to the ground state by magnetic dipole (M1) or electric quadrupole (E2) transitions (denoted 'forbidden transitions'). These second order transitions are generally 10^5–10^8 times weaker than allowed electric dipole (E1) transitions. Higher order transitions, i.e. magnetic quadrupole (M2) or electric octupole (E3) contributions to the decay channels, are generally several orders of magnitude weaker and in most cases negligible.

In the present study, we were interested in the decay properties of the $3s^2 3p^4(^1D)3d\ ^2G_{7/2,9/2}$ levels in Ar^+. These metastable states can decay to lower energy levels of the same configuration and of the $3s^2 3p^4 4s$ configuration via M1 and E2 transitions. More interestingly, they can also be connected to the ground term $3s^2 3p^5\ ^2P^\circ$ through higher order transitions, primarily by E3 transitions. These transitions are expected to appear in the UV region (around 65 nm) and the transition probabilities are likely to be enhanced by a strong wavelength effect like the ones observed in Kr II[1] and Xe II[2]. Contrary to these last two cases however, the M2 decay channel is forbidden by the LS selection rules while the E3 transitions are allowed. The importance of a weak E3 transition has previously been reported for Yb II[3].

Using the CRYRING ion storage ring of Stockholm[4], a laser probing investigation has yielded the lifetimes of the $3s^2 3p^4(^1D)3d\ ^2G_{7/2,9/2}$ metastable doublet of Ar^+. The results are 3.0 ± 0.4 and 2.1 ± 0.1 s, respectively. Comparisons with theoretical values calculated with two independent approaches, i.e. the pseudo-relativistic Hartree-Fock method and the multiconfiguration Breit-Pauli approach, have allowed us to establish the unexpected and extraordinary strong contribution of the E3 transition to the ground state, in addition to the M1 decay channels to the 3d $^{2,4}F$ states and the E2 contributions to the 4s ^2P, ^2D states. It should be emphasized that this E3 transition is the fastest one (of the order of a tenth of a s^{-1}) ever observed in an experiment. This new result has just been published in PRL[5].

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Atomic Data for Heavy Atoms and Ions (72$<Z<$86) : A Progress Report

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Our knowledge of the atomic and ionic spectra of the sixth row elements of the periodic table, from Z=72 to Z=86, is still very poor due to the fragmentory laboratory analyses on the one hand and to the complexity of the electronic configurations of the type $4f^{14}5d^N nln'l'$ (N=2–10, nl,$n'l'$=6s, 6p, 6d, ...) on the other hand.

The aim of the present work is to provide new radiative data (wavelengths, energy levels, oscillator strengths, radiative lifetimes) as accurate as possible for neutral and lowly ionized platinum group elements. Calculations of atomic structures and spectra in such species are frequently the only way to obtain a large amount of atomic data required by the astrophysicists, particularly for the interpretation of the spectra of chemically peculiar stars and for the study of stellar abundances and nucleosynthesis. Spectroscopic data for some of these elements are also strongly needed for research oriented toward controlled thermonuclear fusion. In particular, radiative properties of tungsten ions are important in connection with the use of this element in fusion reactors.

Such atomic structure calculations, extremely complex, need to be tested by comparisons with experiment in order to deduce some informations about their predictive power. For that reason, we have systematically compared the results obtained with our theoretical models, i.e. the Hartree-Fock approach including configuration interactions, relativistic effects and core-polarization corrections[1,2] with new lifetime measurements carried out using the time-resolved laser-induced fluorescence technique developed at the Lund Laser Centre by Prof. Svanberg and his group.

By combining experimental radiative lifetimes and theoretical branching fractions, we have been able to determine many new oscillator strengths and transition probabilities. The results obtained so far concern the following ions : Ta I (Z=73), W II, W III (Z=74), Re I, Re II (Z=75), Os I, Os II (Z=76), Ir I, Ir II (Z=77), Pt II (Z=78), Au I, Au II, Au III (Z=79), Tl I (Z=81) , Pb II (Z=82) and Bi II (Z=83). These results will be stored in the database DESIRE (**D**atabas**E** on **SI**xth **R**ow **E**lements) on a website of the University of Mons-Hainaut[3,4].

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Theoretical Analysis of Precision Calculation of Helium-like Excited Energy Levels

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An atomic system with two electrons is a simple nontrivial many-body system. Many theoretical[1,2,3]. and experimental[4,5] works have been done for excited energy levels of the system. For the low Z ions, both theoretical and experimental studies have achieved a very high precision. However, for the high Z ions, the experimental measurements[5] have very large uncertainties while the theoretical calculations may have not considered adequate electron correlations[2,3], relativistic[1] and QED effects[1−3].

In this letter, we analyze our multi-configuration Dirac-Fock(MCDF) calculations of $2^3P_{0,1,2}$ and 2^1P_1 states along Helium isoelectronic sequence[3] quantitatively by an effective Hamiltonian(with approximate physical parameters) which should be valid in all coupling schemes. The physical parameters have their own physical meanings. Our analysis results show that, for lower Z ions, the correlations are the most important effects for the calculation precision and can be precisely corrected based on our MCDF calculations. The competition between Breit and spin-orbit interactions causes interesting variations of $2^3P_{0,1,2}$ fine structure orderings[3]. However, for high Z ions, Breit interactions which represent the relativistic retardation effect of electromagnetic interactions and high order QED corrections are the most important effects for the calculation precision. Such analysis results would be useful for further theoretical precision calculations as well as experimental studies for high Z Helium-like ions, such as the storage ring experiments.

Our analysis is based on the framework of full relativistic QED theory in the Coulomb gauge. For the Dirac-Coulomb and Breit interactions of these states, we use 9 parameters to construct the effective Hamiltonian, as shown in eq.1. Here, a scales as Z^2 and is the statistical average of the 4 excitation energies; b scaling as Z represents the exchange correlations; δ_{so} scales as Z^4 and is for the spin-orbit splittings between $p_{1/2}$ and $p_{3/2}$; d scales as Z and is for relativistic corrections[6] of $p_{1/2}$ and $p_{3/2}$ and $q, \overline{q}, q^*, \overline{q}^*, q'$ scaling as Z^3 are for Breit interactions. Since the high order QED corrections(Self Energy, Vacuum Polarization, etc.) are mainly for single electron, we use one QED parameter for each energy level. The high order QEDs in this work are taken from Drakes results[1] the same way as Johnson did[2]. The high order QED corrections mainly scale as Z^4.

When Z is low, our correlation corrected excitation energies agree with NIST's[7] within 1cm^{-1}; when Z is very high, eg, U^{90+}, the correlation effect is nearly a hundredth of Breit interactions and high order QED effects. Therefore for high Z ions, the Breit and high order QED effects are the most important. Breit interactions can be treated well in our MCDF calculations but further efforts should be made in the high order QED calculations.

$$H_{J=1} = \begin{bmatrix} a - 5b/12 + \delta_{so}/2 - d + q^* & \sqrt{2}b/3 + q' \\ \sqrt{2}b/3 + q' & a - b/12 - \delta_{so} + d + \overline{q}^* \end{bmatrix} \quad \text{and} \quad \begin{cases} H_{J=2} = a + b/4 + \delta_{so}/2 - d + q \\ H_{J=0} = a + b/4 - \delta_{so} + d + \overline{q} \end{cases} \tag{1}$$

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High-Resolution Laser Spectroscopy of a Bose Einstein Condensate Using the Ultranarrow Magnetic Quadrupole Transition

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The study of laser-cooled two-electron atoms is one of the most interesting research fields in atomic physics. In particular, the unique characteristics of the metastable $^3P_2$ state of two-electron atoms have recently attracted attention both for their applications and study of their intrinsic characteristics.

We report the successful observation of the ultranarrow magnetic quadrupole $^1S_0 \leftrightarrow {}^3P_2$ transition in Ytterbium (Yb) (Fig. 1). We first developed a novel 507-nm laser source. By tightly locking the laser frequency to a high-finesse external optical cavity, we stabilized the laser frequency and reduced the linewidth to less than 1 kHz [1]. Using this laser source, we observed the $^1S_0 \leftrightarrow {}^3P_2$ transition in Yb bosonic (^{174}Yb) and fermionic (^{171}Yb, ^{173}Yb) isotopes. High-resolution spectroscopy of ultracold atoms and a BEC was performed using this ultranarrow transition. The transition from the Doppler-broadened spectra of thermal atoms to the asymmetric spectra reflecting the inhomogeneous density distribution of BEC in a harmonic trap has been successfully observed (Fig. 1).

We acknowledge Y. Li and M. Hosokawa for their experimental assistances.

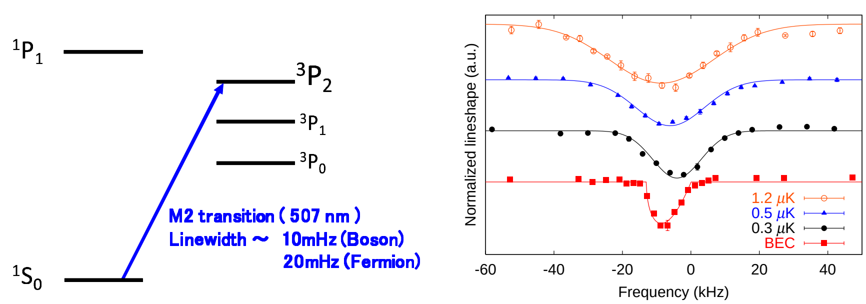

Figure 1: *(Left) Relevant energy levels for Ytterbium. (Right) Observed spectra of the* $^1S_0 - {}^3P_2$ $(m = 0)$ *transition in ultracold* ^{174}*Yb atoms and a BEC. A sudden change of the spectrum below the BEC transition is due to the large mean field energy of a BEC.*

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High efficiency frequency upconversion in rubidium vapor

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A two-photon near resonant excitation of the Rubidium $5D_{5/2}$ level with 780nm and 776nm pump beams (Fig. 1) leads to the generation of a coherent beam of 420 nm blue light via four-wave mixing due to the strong dipole moment of the 5 μm channel. We have recently obtained more than 1 mW of coherent blue light, exceeding powers in previous experiments[1,2] by a factor of 20 for comparable input powers. We investigate the optimum conditions for the generation of the blue light, and observe that blue power linearly increases with 776 nm power.

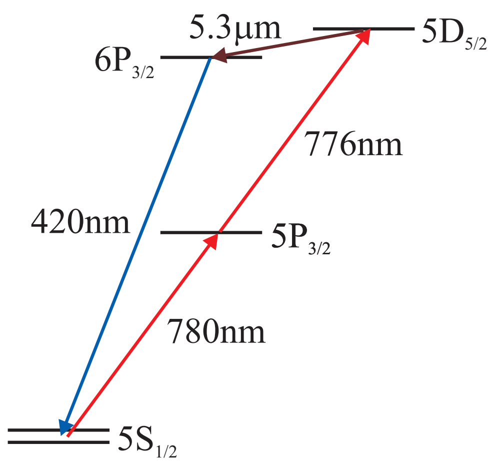

Figure 1: *Rubidium level scheme relevant for blue-light generation.*

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Two photon spectroscopy in atomic hydrogen at 205 nm using a picosecond laser

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Atomic hydrogen is the simplest atomic system containing one proton and one electron. The dipole forbidden 1s-2s transition in Hydrogen with a natural linewidth of 1.3 Hz in combination with Doppler-free two photon spectroscopy acts since decades as benchmark for Quantum electrodynamic calculations. For example the Lamb shift measurements of the 1s state started with a relative uncertainty of 9×10^{-2} in 1975 [1] and reached a level of 2.7×10^{-6} in the latest experiments [2].

To improve the accuracy of the 1s Lamb shift and also of the Rydberg constant a measurement of the 1s-3s transition frequency is prepared. For the two photon spectroscopy a wavelength of 205 nm is neccessary, which is produced by two successive second harmonic generations. Using mode locked lasers and resonant second harmonic generation makes the conversion more efficient. As proposed in 1977 [3] a mode locked laser with narrow pulses and its regular mode spectrum can also be a good tool for first order Doppler-free two photon spectroscopy. The frequency modes of the laser adds up in such a way that the linewidth of the resonance is determined by the width of a single mode and not by the pulse duration and the resonance intensity corresponds to the average laser power.

In the presented experiment a commercial picosecond Ti:Sa laser operating at 820 nm is resonantly frequency doubled to 410 nm and in second enhancement cavity the 205 nm is produced. Starting with 1.6 W at 820 nm an output power of 40 mW at 205 nm is achievable [4]. The UV light is further enhanced in linear cavity, designed in such a way that two counterpropagating pulses overlap in the middle of the cavity, where the hydrogen beam crosses the laser beam. The atomic hydrogen beam is produced by a rf-discharge and cooled down to liquid helium temperature to reduce transit time broadening. The excited atoms can decay over the 3s-2p transition at 656 nm that is detected by a photomultiplier.

In the presentation an overview of the setup and the current status is given.

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Laser spectroscopy in wall-coated alkali vapour cells

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In the fifties pioneering works [1] demonstrated that coating the walls of a glass cell with chemically inert substances reduce the relaxation of the atomic polarization improving the resolution in high precision spectroscopy and metrology. Recently the interest in wall-coated cells is growing again because coated cells represent a good candidate to realize high-performance or micro-quantum sensors[2].

In this communication we report on our preliminary results in laser spectroscopy in paraffin wall-coated Rb vapour cells. In particular we discuss some quality test of the cell based on absorption spectroscopy and our experiments on hyperfine Coherent Population Trapping[3] spectroscopy.

During the experiments, the cell is placed inside both an active and passive magnetic shields (shielding factor $< 10^{-3}$) and a solenoid is used to apply a longitudinal magnetic field on the atomic sample. In the absorption spectroscopy experiments we use single-frequency diode laser and for the CPT experiments the diode laser is modulated through an Electro-Optical Modulator for obtaining the two coherent frequencies necessary to pump the atoms into a dark state.

We are investigating on the possibility to exploit the dependence of the absorption spectrum on the excitation time for first evaluation of the coating quality. The simplicity of this approach from both theoretical and experimental point of view makes it interesting. On the other hand absorption spectroscopy is a relatively low sensitivity technique limiting the information we can get from it. In view of future application in CPT-based atomic clocks, we address our attention to the study of hyperfine ground state coherence relaxation, that has been not systematically studied much so far. Here we discuss the CPT signal linewidth and amplitude depending on some relevant experimental parameters, as the intensity and the linewidth of the laser, and the cell volume. The results are compared with data on Zeeman relaxation obtained in DROM configuration [4].

We thank A. Weis and N. Castagna for the joint DROM measurements and our colleagues of LTF for the useful discussion. This work is supported by the Association Suisse pour la Recherche Horlogère (ASRH), by Swiss National Science Foundation (project 200020-105624) and by the INTAS-CNES (project 06-1000024-9321).

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A high-power, Fourier-transform limited light source for precision spectroscopy in the XUV

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High-resolution laser spectroscopy in the XUV requires pulsed, tunable light sources with high peak powers and narrow optical bandwidths for nonlinear-optical upconversion to generate the required wavelengths. For instance, the $2\,^1S \leftarrow 1\,^1S$ two-photon absorption transition of helium (He) has been measured with narrowband 120-nm radiation generated by pulsed dye amplification of a cw tunable Ti:sapphire laser, followed by nonlinear-optical upconversion.[1]

However, the precision of these VUV spectroscopic studies was limited by degradation of near-infrared optical bandwidth arising from the pulsed dye amplification processes.[1] This arose from shot-to-shot fluctuations in the frequency of the laser pulse (e.g., due to thermal lensing and dye flow inhomogeneities), as well as frequency chirping attributable to the changes in the population inversion of the dye during the pulse.

To circumvent such bandwidth limitations, we employ a high-performance injection-seeded optical parametric oscillator (OPO) based on periodically poled $KTiOPO_4$ (PPKTP) and generating narrowband tunable light pulses at $\sim$840 nm with $\leq$5 μJ energy.[2,3] Population inversion cannot contribute to frequency chirping in this nonlinear-optical approach, which yields well-characterized shot-to-shot frequency stability. Our next step is to amplify the OPO output prior to nonlinear-optical upconversion from $\sim$840 nm to $\sim$210 nm and, ultimately, to $\sim$120 nm.

With the Ti:sapphire-amplified SLM pulsed OPO output at $\sim$840 nm fully characterized, we aim to upconvert it to $\sim$210 nm by successive second-harmonic-generation stages and to test the outcome by recording sub-Doppler two-photon laser-induced fluorescence spectra of krypton (Kr) excited to its $5p[1/2]_0$ state (at $\sim$212.6 nm) and/or of nitrogen (N_2) excited to its $E\,^3\Sigma_g^+$ state (at $\sim$209 nm). Spectroscopic performance tests are considered crucial, as in our previous work on sub-Doppler two-photon spectra of cesium (Cs) at $\sim$822 nm.[3]

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Large scale CIV3 calculations of fine-structure energy levels and lifetimes in Co XV

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We have performed large scale CIV3 calculations of excitation energies from ground states for 98 fine-structure levels as well as of oscillator strengths and radiative decay rates for all electric-dipole-allowed and intercombination transitions among the fine-structure levels of the terms belonging to the $(1s^22s^22p^6)3s^23p$, $3s3p^2$, $3s^23d$, $3p^3$, $3s3p3d$, $3p^23d$, $3s3d^2$, $3p3d^2$, $3s^24s$, $3s^24p$, $3s^24d$, $3s^24f$, and $3s3p4s$ configurations of Al-like Cobalt, using very extensive configuration-interaction (CI) wave functions[1]. The important relativistic effects in intermediate coupling are incorporated by means of the Breit-Pauli Hamiltonian which consists of the non-relativistic term plus the one-body mass correction, Darwin term, and spin-orbit, spin-other-orbit, and spin-spin operators[2]. The errors, which often occur with sophisticated *ab initio* atomic structure calculations, are reduced to a manageable magnitude by adjusting the diagonal elements of the Hamiltonian matrices. In this calculation we have investigated the effects of electron correlations on our calculated data, particularly on the intercombination transitions, by including orbitals with up to n=5 quantum number. We considered up to three electron excitations from the valence electrons of the basic configurations and included a large number of configurations (1164) to ensure convergence.

Our calculated excitation energies, including their ordering, are in excellent agreement with the experimental results[3] and the experimentally compiled energy values of the National Institute for standards and Technology (NIST) wherever available. The mixing among several fine-structure levels is found to be very strong, with most of the strongly mixed levels belonging to the $(1s^22s^22p^6)3p^23d$ and $3s3d^2$ configurations. In our CIV3 calculation we identify the levels by their dominant eigenvector[4]. The enormous mixing among several fine-structure levels makes it very difficult to identify them uniquely. Perhaps, this may be the reason that no experimental results are available for these levels. Our very extensive calculations may assist the experimentalists in identifying these fine-structure levels. From our transition probabilities, we have also calculated radiative lifetimes of the fine-structure levels in Co XV. Our calculated lifetime for the level $3s3p^2(^4P_{0.5})$ is in excellent agreement with the experimental value compared to other sophisticated theoretical result. We predict new data for several levels where no other theoretical and/or experimental results are available.

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Fine-structure energy levels and radiative rates for transitions in Mg-like Copper

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Emission lines of Mg-like ions are observed in a variety of solar and astrophysical plasmas, and are detected from the UV to the X-ray band. Their emission lines are also widely detected in the spectra of laboratory plasmas, including tokamaks, and are of particular interest in controlled thermonuclear fusion, because they help to estimate the energy loss from the impurities of the reactor walls. Atomic data for parameters such as energy levels, oscillator strengths, radiative decay rates, and collision strengths are required to interpret the plasma observations.

We have performed large scale CIV3 calculation of energy levels and radiative rates for electric dipole transitions among the lowest 141 levels of the $(1s^2 2s^2 2p^6)3l^2$, $3l3l'$ and $3l4l$ configurations of Cu XVIII. These states are represented by very extensive configuration-interaction (CI) wave-functions obtained using the CIV3 computer code of Hibbert[1]. The important relativistic effects are included through the Breit-Pauli approximation[2]. In order to keep the calculated energy splittings close to the experimental values, we have made small adjustments to the diagonal elements of the Hamiltonian matrices.

Our adjusted excitation energies, including their ordering, are in excellent agreement (better than 1%) with the available experimental results[3]. Since mixing among several fine-structure levels is found to be very strong, it becomes difficult to identify these uniquely. In our CIV3 calculations we identified these levels by their dominant eigenvector[4]. From our transition probabilities, we have also calculated radiative lifetimes of some fine-structure levels. Our calculated oscillator strengths, radiative decay rates and the lifetimes are found to be in good agreement with the experimental and other theoretical results (wherever available). We predict new data for several levels where no other theoretical and/or experimental results are available.

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A new method for determining minute long lifetimes of metastable levels

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Radiative lifetime measurements of metastable states have been performed for many years utilizing stored ions. When measuring lifetimes of metastable states in a storage ring the signal may be greatly enhanced, compared to that from passive observation, by actively inducing transitions with one or more lasers. The basic principle of our laser probing technique has been to probe the population of the metastable state as a function of delay time after ion injection which gives us a population decay curve, see *e.g.* Ref. [1]. The introduction of lasers also increases the maximum possible measurable lifetime significantly. Currently the longest radiative lifetime measured at the storage ring CRYRING in Stockholm, Sweden, and to the best of our knowledge in storage rings in general, is 89 s in BaII, see Ref. [2]. For lifetimes longer than this collisional excitation of stored ground state ions becomes a problem since after a few seconds of storage the vast majority of the population of the metastable state under study will be originating from ions that were in the ground state when injected into the storage ring. During the analysis, this contribution is subtracted from the total fluorescence which gives a low S/N ratio, large uncertainties and eventually limits the maximum possible lifetime measurable.

A new method has therefore been proposed and its advantages concerning more accurate lifetime determinations of extremely long lived metastable states demonstrated, see Ref. [3]. Instead of monitoring the decay of the population of the metastable state relative to ion injection the contribution from collisional excitation is monitored directly. In contrast to the metastable state population itself, the collisional excitation grows stronger with increased storage time which results in a much higher S/N ratio at longer storage times and higher residual gas pressures and as a consequence the maximum possible radiative lifetime measurable increases. This technique has so far only been applied in two studies with lifetimes ranging from 16 to 32 s, the 5d $^2D_{5/2}$ state in BaII, see Ref. [3], and the b $^4P_{5/2}$ state in TiII, submitted to J Phys B. This new technique has not yet been pushed to its limit but lifetimes of a few minutes will most probably be possible to measure.

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Theoretical and Experimental Study of Polarization Spectroscopy of Rubidium Atoms

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We present an experimental and theoretical (numerical and analytic) study on polarization spectroscopy (PS) of rubidium. The laser-induced birefringence was observed by using linearly polarized probe beam and circularly polarized pump beam. We performed a theoretical calculation of PS spectral based on the rate equation model. All the populations of the magnetic sub-levels were calculated from the rate equations, and used in the calculation of the polarization spectra. Using this model, we could generate theoretical line shapes to make predictions about the general form of the polarization spectra for the D_2 transition of Rb atoms. By comparing theoretical and experimental spectra, we found high agreement in our calculations and experimental data [1].

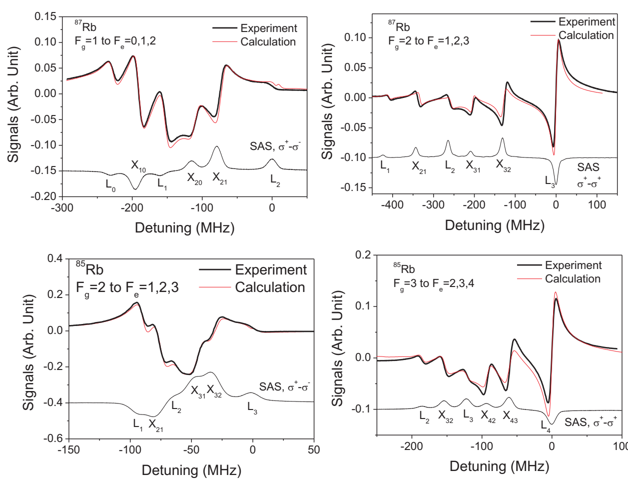

Figure 1: *The experimental and calculated PS spectra for the ^{87}Rb atoms and ^{85}Rb atoms.*

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New data, spin-orbit functions, and potential energy curves for the $A\ ^1\Sigma_u^+$ and $b\ ^3\Pi_{0u}$ states of Cs_2 and Rb_2

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The lowest alkali dimer excited states, $A\ ^1\Sigma_u^+$ and $b\ ^3\Pi_{0u}$, are of particular interest as pathways to the higher states and in the creation of ultracold molecules. The study of these states for the heavy molecules as Cs_2 and Rb_2 is relatively complicated due to the large spin-orbit interactions which mix their potentials. In this study, new data added to the already existing data have been modeled using the Discrete Variable Representation (DVR), so as to fit potential energy and spin-orbit functions.
With the help of high resolution Fourier spectra measured recently at Lyon, we have produced and improved the fit of all available data for the Rb_2 $A\ ^1\Sigma_u^+$ and $b\ ^3\Pi_{0u+}$ states. Vibrational assignments in the A state are unambiguously established and in the b state are strongly probable; we have shifted T_e of the b state by $\pm n\omega_e$ until achieving the best fit. Currently, the rms residual of our fit is 0.07 cm^{-1} while the experimental uncertainty was estimated to be 0.005 cm^{-1}. The potentials are represented by the "Hannover" form.
New low resolution data on Cs_2 $b\ ^3\Pi_{0u\pm}$ states have been obtained in Tsinghua University. Adding these data to data previously obtained from Lab. Aimé Cotton on mixed $A \sim b$ states[1,2] has permitted us to characterize the bottom of the potential wells of both the A and the b states. Application of a Morse-Long Range potential[3] has improved the fit in comparison to the Hannover form usually used with DVR method. Currently the rms residual of our fit to the new low resolution data is 1.65 cm^{-1} ($\sim$ experimental uncertainty) and 0.08 cm^{-1} to the older Fourier transform spectroscopy data which has experimental uncertainties of 0.003 cm^{-1}. To reach the levels observed by photoassociation of Feshbach resonances[4], we were forced to extrapolate our potential through a gap of $\sim$800 cm^{-1}, which resulted in a degradation of the rms residual to 0.2 cm^{-1}. Undoubtedly, additional data would be useful, both in regions where no levels have yet been observed, and where few levels with dominant triplet character have been identified.

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Laser Spectroscopy of Exotic Helium Isotopes

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We have succeeded in laser trapping and cooling of the exotic helium isotopes ^{6}He ($t_{1/2}$ = 0.8 sec) and ^{8}He ($t_{1/2}$ = 0.1 sec), and have performed precision laser spectroscopy on individual trapped atoms. Based on the atomic isotope shifts measured along the isotope chain ^{3}He - ^{4}He - ^{6}He - ^{8}He, and on the precise theory of the atomic structure of helium, the nuclear charge radii of ^{6}He and ^{8}He are determined for the first time in a method independent of nuclear models. The results are compared with the values predicted by a number of nuclear structure calculations and test their ability to characterize these neutron rich, loosely bound halo nuclei. The ^{6}He measurement[1] was performed at ATLAS of Argonne, and the ^{8}He measurement[2] at GANIL, France.
We also report measurements made on ^{3}He where we investigated anomalous strengths of transitions from the metastable 2^3S to the 3^3P manifold[3]. We understand this to be a consequence of strong hyperfine mixing because the hyperfine structure is of the same order of magnitude as the fine structure in ^{3}He.

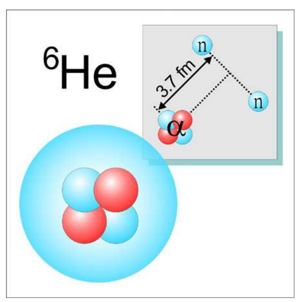

Figure 1: *He-6 nuclei are thought to consist of a He-4 inner core and an outer "halo" part consisting of two more neutrons. The isotope shift measurements reported[1,2] are sensitive to the RMS distance between the alpha particle core and the neutron halo, for both He-6, and He-8.*

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[3]In preparation

Assignment of the RbCs $2^3\Pi_0$, $2^3\Pi_1$, and $3^3\Sigma_1^+$ states and perturbations

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Alkali metal diatomic molecules have been broadly investigated, both experimentally and theoretically, and have attracted much attention from various fields such as molecular spectroscopy, photodissociation dynamics, and photoassociation spectroscopy. Particularly, recent rapid progress in experiments with ultracold molecules has mainly focused on the heteronuclear alkali dimers since they can be applied to qubit generators for quantum computation.[1] Recently, the low-lying strongly coupled $1^1\Pi$-$2^3\Sigma^+$-$1^3\Pi$ system of heteronuclear alkali dimer RbCs was employed for producing ultracold $X^1\Sigma^+$ RbCs molecules.[2]
We report a newly identified parallel transition of $2^3\Pi_0 \leftarrow X^1\Sigma^+$ and coupled perpendicular transitions of $2^3\Pi$, and $2^3\Pi_1$, $3^3\Sigma_1^+ \leftarrow X^1\Sigma^+$ and observed by mass-resolved resonance enhanced two-photon ionization (RE2PI) in a cold molecular beam of RbCs. Very complex vibronic structures have been observed in our RE2PI spectrum near 640 nm. The $2^3\Pi_0$ state, however, shows a very regular vibronic structure, indicating the absence of significant perturbation. By fitting the observed term values of these parallel bands, we have determined the molecular constants and the Rydberg-Klein-Rees (RKR) potential energy curve of the $2^3\Pi_0$ state.
The origin of the complex vibronic structures has been attributed to strong spin-orbit interactions among the Ω = 1 states. In the lower energy spectral region where the onsets of the $2^3\Pi_1$ and $3^3\Sigma_1^+$ $\leftarrow X^1\Sigma^+$transitions were observed, we have identified the electronic symmetry and the vibrational quantum numbers of the upper vibronic states for the observed perpendicular bands. The diagonal spin-orbit interaction constant of the $2^3\Pi$ state has been estimated from the observed splitting of the electronic term values of the Ω= 0 and 1 components.

The authors are grateful to Dr. Stolyarov for many helpful discussions.

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Light interactions in Rydberg ensembles

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Atoms in highly excited Rydberg states exhibit strong interactions over distance scales of a few microns. In our work we exploit the enhanced sensitivity of Rydberg states to control the propagation of light through an atomic ensemble. For example, if the atoms are prepared in a dark state corresponding to a superposition of ground and Rydberg states[1] the medium acquires a giant electro-optic effect many orders of magnitude larger than other systems[2]. This giant electro-optic effect can be used to impose sidebands on light propagating through the ensemble as shown in Figure 1a). In ultra-cold ensembles we have observed Rydberg dark states with linewidths of less than 1 MHz (see Figure 1b) and have demonstrated the on-set of interactions effects as the Rydberg density is increased[3]. Our eventual goal is to exploit this giant non-linearity to control pulse propagation at the single photon level.

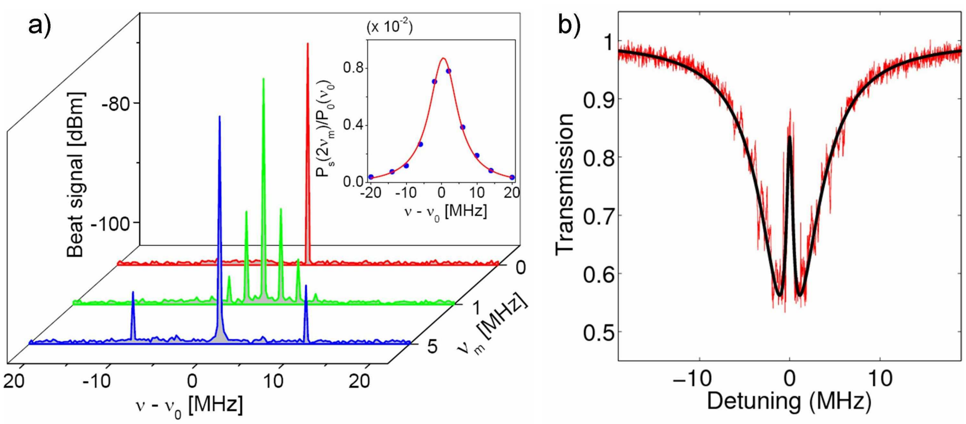

Figure 1: *a) Power spectrum of light transmitted through the Rydberg dark state ensemble showing the generation of sidebands at the* $2^{\rm nd}$ *harmonic of an applied electric field modulation with amplitude* $3\ \mathrm{V/cm}$ *and frequency* $\nu_{\rm m}$. *Kerr coefficients* $> 10^{-6}\ \mathrm{m/V^2}$ *are measured. Inset: Frequency response of the dark state resonance determined from the sideband intensity. (b) Narrow EIT resonance corresponding to the* $\mathrm{n} = 26\mathrm{d}$ *state in a cold Rb sample. Linewidths of* $\sim\ 600\ \mathrm{kHz}$ *are observed.*

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Theoretical study of the hyperfine structure and isotope shifts in near-infrared transitions of atomic nitrogen

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Doppler-free spectra of N I transitions on the $2p^2(^3\mathrm{P})3s\ ^4\mathrm{P} \rightarrow 2p^2(^3\mathrm{P})3p\ ^4\mathrm{P}^o$, $^4\mathrm{D}^o$ multiplets have been recorded by Jennerich *et al.* [1] using saturated absorption spectroscopy. From these data, Jennerich *et al.* extracted values for the hyperfine structure coupling constants for the various J levels of these multiplets, for both ^{14}N and ^{15}N. Isotope shifts of three transitions in each multiplet have also been measured, revealing a significant J-dependence of the shifts. These authors recommended a theoretical investigation of the undelying cause of this unexpected phenomenon.

In the present work, we report ab initio calculations of hyperfine structure and specific mass shift parameters, together with transition data using the ATSP2K package[2]. Elaborate correlation models within a systematic appoach are used for assessing the reliability of the ab initio parameters. Experimental isotope shift values are critically dependent on the correct interpretation of the hyperfine structures of the ^{14}N and ^{15}N spectra. The specific mass shift parameters calculated for $2p^2(^3\mathrm{P})3p\ ^4\mathrm{P}^o$ and $^4\mathrm{D}^o$ are almost identical and it is hard to propose any mechanism that would cause the observed J-dependency of the isotope shifts. The calculated hyperfine structure constants strongly disagree with experiments, suggesting at this stage that the origin of the problem might be the analysis of the observed hyperfine structures.

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Two-photon spectroscopy of ^{88}Sr

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We report two-photon photoassociative spectroscopy (PAS) of atomic ^{88}Sr utilizing intermediate states that are weakly bound on the $^1S_0 - {}^3P_1$ potential and determination of the s-wave scattering length a for ^{88}Sr. Two-photon PAS is a powerful tool that finds various applications such as the production of ultracold bound molecules and has been employed to measure the binding energy of weakly bound levels of ground molecular potentials. Furthermore, due to the metastability of the $^3P_1$ state the shape of the excited molecular potential and values of the molecular Franck-Condon factors and atomic dipole matrix elements make spectroscopy near the $^1S_0 - {}^3P_1$ transition differ qualitatively than when using a dipole-allowed transition. Each of these measurements provides accurate determination of a and an understanding of the paths towards quantum degeneracy and the behavior of resulting quantum fluids.

Absolute absorption on the rubidium D lines: comparison between theory and experiment

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Having a theoretical model which predicts the absorption and refractive index of a medium is useful, for example, in predicting the magnitude of pulse propagation effects. We study the Doppler-broadened absorption of a weak monochromatic probe beam in a thermal rubidium vapour cell on the D lines[1]. A detailed model of the susceptibility is developed which takes into account the absolute linestrengths of the allowed electric dipole transitions and the motion of the atoms parallel to the probe beam. All transitions from both hyperfine levels of the ground term of both isotopes are incorporated. The absorption and refractive index as a function of frequency are expressed in terms of the complementary error function. The absolute absorption profiles are compared with experiment, and are found to be in excellent agreement provided a sufficiently weak probe beam with an intensity under one thousandth of the saturation intensity is used. The importance of hyperfine pumping for open transitions is discussed in the context of achieving the weak-probe limit. Theory and experiment show excellent agreement, with an rms error better than 0.2% for the D_2 line at 16.5°C (see Fig. 1).

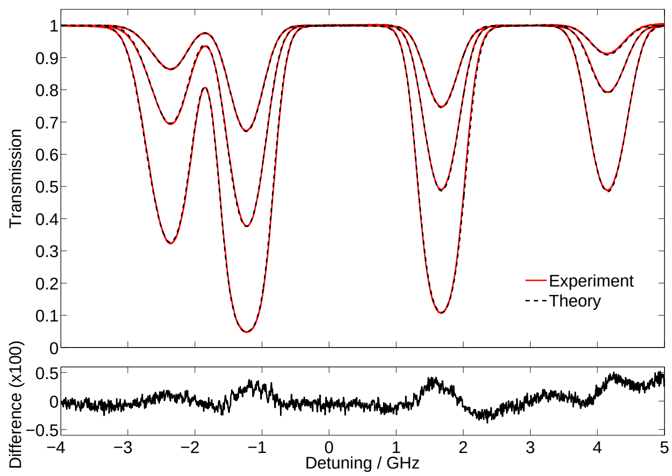

Figure 1: *Transmission plots for the comparison between experiment and theory, at temperatures of $16.5°C$ (top), $25.0°C$ (middle), and $36.6°C$ (bottom). Red and black lines show measured and expected transmission respectively. Below the main figure is a plot of the difference in transmission between theory and experiment for the $16.5°C$ measurement.*

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Optical pumping effect on the magnetic field dependent intensity of hyperfine split D_1, D_2 lines of ^{85}Rb and ^{87}Rb

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The intensity of Zeeman components of rubidium (^{87}Rb and ^{85}Rb) hyperfine split D_1 and D_2 lines has been studied up to a field of 5mT. Saturation absorption spectroscopic technique is used to resolve the hyperfine spectrum. Optical pumping effect in the closed transition (F=2 to F'=3 in ^{87}Rb and F=3 to F'=4 in ^{85}Rb D_2 line) is reported. All possible polarization configurations (π, σ_+, σ_-) have been employed for the pump and probe beams. Tremblay's field induced transition probability[1], Nakayama's four level model[2] were already used by us to compute the field dependent intensity variation[3]. These calculations have now been refined taking into account multi- cycle pumping[4]. The experimental and calculated results are compared.

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Saturation spectroscopy of the 372 nm Fe I resonance line with laser diode radiation

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Saturation spectroscopy is a well known technique to get Doppler-free spectral lines of elements at ultra-high resolution. It is also a popular technique to stabilize precisely laser radiation within atomic linewidths. Here we report preliminary results about absorption saturated spectra of the resonance line $3d^6 4s^2\,{}^5D_4 \rightarrow 3d^6 4s4p\,{}^5F_5^o$ of iron atoms at 371.9935 nm using a low power commercial laser diode. The scheme of the experimental setup is shown on Fig. 1. A UV laser diode delivering a 4 mm^2 5 mW laser beam is sent partly to a saturation spectroscopy setup and crosses an iron vapor cell. Iron atoms are produced in a home made Fe-Ar hollow cathode discharge cell[1]. The laser beam is sent backwards to the hollow cathode and is superimposed exactly to the pump beam in combination with a $\lambda/4$ waveplate to extract the 90° polarization rotated probe beam at the exit of the hollow cathode. Good signal to noise ratios in the saturated absorption spectra have been obtained, demonstrating the suitability of commercial UV laser diodes for this purpose and their ability to be easily stabilized at this wavelength for any application requiring such radiation. In this way we extend to small UV laser diode systems the results obtained by Smeets *et al.*[2] with a doubled frequency titanium sapphire laser.

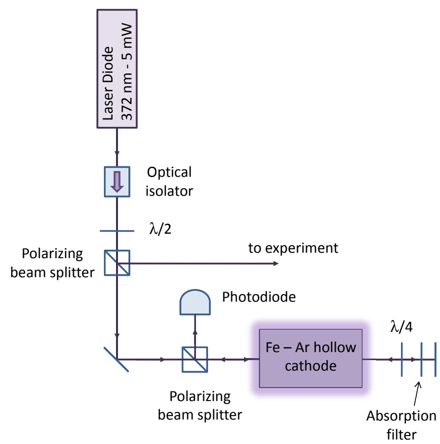

Figure 1: *Experimental arrangement.*

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Potassium ground state scattering parameters and Born-Oppenheimer potentials from molecular spectroscopy

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We present precision measurements with MHz uncertainty of the energy gap between asymptotic and well bound levels in the electronic ground state X $^1\Sigma_g^+$ of the $^{39}K_2$ molecule. The molecules are prepared in a highly collimated particle beam and are interrogated in a Λ-type excitation scheme of optical transitions to long range levels close to the asymptote of the ground state, using the electronically excited state A $^1\Sigma_u^+$ as intermediate one.[1] The transition frequencies are measured either by comparison with I_2 lines or by absolute measurements using a fs-frequency comb. The asymptotic levels were observed for the first time and extend the existing datafield[2] to within 0.2 cm^{-1} of the dissociation energy. The determined level energies were used together with Feshbach resonances from cold collisions of ^{39}K and ^{40}K reported from other authors[3] to fit new ground state potentials. Precise scattering lengths are determined and tests of the validity of the Born-Oppenheimer approximation for the description of cold collisions at this level of precision are performed. This is of particular importance if one aims for describing Feshbach resonance positions of several isotope combinations by a single model.

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Tomography of a cold molecular beam via cavity-enhanced direct frequency comb spectroscopy

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The emerging field of cold molecules and cold chemistry will require spectroscopic probes capable of investigating large energy scales at high resolution[1]. Cavity-enhanced direct frequency comb spectroscopy combines broad spectral bandwidth, high spectral resolution, precise frequency calibration, and high detection sensitivity, all in one experimental platform[2]. This spectrometer is ideal for studies of the quantum state distributions, density profiles, velocity distributions, and interactions of cold molecular ensembles. To develop and refine this novel spectroscopic technique we have performed tomographic studies of a supersonically cooled beam of acetylene molecules[3]. Absorption measurements are recorded at a variety of positions within the supersonic jet allowing for a direct observation of beam dynamics. A high resolution spectrometer in cavity transmission records 25 nm snapshots of the molecular absorption spectrum while providing resolutions as low as 200 kHz (Fig. 1). The broad bandwidth and high resolution allow for simultaneous observation of internal state distributions and external degrees of freedom as the beam cools (Fig. 2a,d). An inverse Abel transform is applied to the integrated absorption measurements to generate molecular density profiles revealing the internal and external state dependances of the molecular density within the beam[4] (Fig. 2b,c).

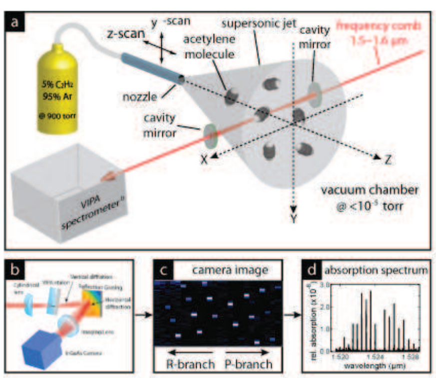

Figure 1. (a) The experimental setup. (b) VIPA spectrometer. (c) Camera image revealing molecular absorption. (d) C_2H_2 absorption spectrum generated by unwrapping camera image.

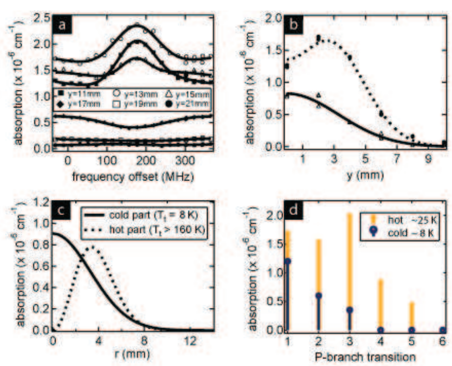

Figure 2. (a) Scan of (ν1+ν3)-R(0)-line over one cavity FSR for different height positions. (b) Hot and cold portions of the beam. (c) Inverse Abel transform, representing radial absorption distributions. (d) P-branch rotational distributions for hot and cold velocity groups.

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Analytic Solutions for the Saturated Absorption Spectra at low intensity

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We present analytic solutions for the saturated absorption spectroscopy(SAS) spectra based on a rate equation model. The model can provide accurate SAS spectra under all experimental conditions (for various pump beam intensities and diameters) without the need for phenomenological constants. The rate equations governing the dynamics of the populations in the presence of a pump laser beam were solved analytically. The SAS spectra were then calculated using the analytic solutions of the populations. The calculation was carried out for the D_2 transition line of the ^{87}Rb atom. One of the assumptions of this method is the large energy spacing between the hyperfine levels of the excited state, which means that the optical pumping to other excited state hyperfine levels can be neglected. Therefore, this method can be better applied to ^{87}Rb or Cs rather than ^{85}Rb or Na. The polarization scheme of the pump and probe beams under consideration is $\sigma^+ - \sigma^+, \sigma^+ - \sigma^-, \pi \parallel \pi$ and $\pi \perp \pi$. We compared the analytic solutions with the numerical and experimental results and found good agreement between them[1].

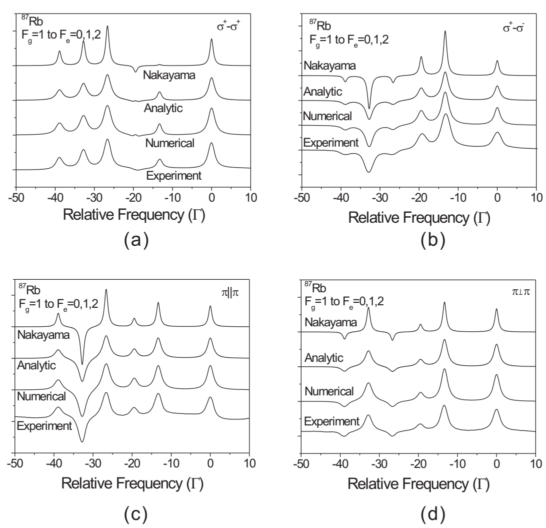

Figure 1: *Experimental, numerical, analytic, and Nakayama's results for the SAS spectra at the transition $F_g = 1 \rightarrow F_e = 0, 1, 2$ when the pump-probe polarization configurations are (a)$\sigma^+ - \sigma^+$, (b)$\sigma^+ - \sigma^-$, (c)$\pi \parallel \pi$, and (d)$\pi \perp \pi$.*

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Cold Atoms Microwave Frequency Standards in Brazil

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Our group has been working in the development of primary frequency standards. These include experiments with Cs atoms in an atomic fountain and cold atoms within a microwave cavity. This last concerns the construction of a magneto-optical trap inside a microwave cylindrical cavity, tuned to the $F = 3, m_f = 0 \rightarrow F = 4, m_f = 0$ ground state transition, and we will report the last advances on it. We worked in a model to explain the poor contrast we observed in preliminary tests using cold atoms and a microwave antenna. This model includes the microwave field distribution and the free expansion of the cold atoms cloud. It was applied to both one and two oscillatory fields interrogation methods, showing good agreement with the acquired data. The other experiment concerns the development of an atomic fountain to be used as a frequency standard. We report the last results obtained for this system, related to first stability evaluations and analysis of frequency shifts. We will also show the structure that is under development to provide capabilities of evaluating these standards and a future link with TAI (International Atomic Time).

Investigation of the optical transition in the ^{229}Th nucleus: Solid-state optical frequency standard and fundamental constant variation

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The technological impact of atomic clocks has been profound. High-precision clocks have also provided a means to probe fundamental issues in physics. Already, atomic clock experiments have provided some of the most stringent tests of General Relativity[1] and produced the tightest constraints on present day variation of many of the fundamental constants[2]. It appears universally recognized that the most promising route to improved clocks uses reference oscillators based on optical transitions; already, two such experiments have reported better stability than the primary Cs standard[2,3].

Despite their successes, traditional clock experiments are often cumbersome. To mitigate environmental influences on the reference oscillator transition, modern clock experimenters routinely employ complicated interrogation schemes such as atomic fountains or optical lattice confinement. An interesting shift in paradigm is to consider an optical clock based on a nuclear transition. Just as in atomic clocks, the high Q oscillator, *i.e.* the nuclear transition, can in principle be addressed by laser spectroscopic techniques, as long as the transition energy is accessible with current laser technology. However, as is well-known from Mössbauer spectroscopy, nuclear transitions are relatively insensitive to their environmental surroundings compared to atomic transitions. Thus, the complicated apparatus of an optical atomic clock may be replaced by a single room-temperature crystal doped with an appropriate nucleus.

We present a proposal for the the construction of a frequency standard based on an optical transition in the ^{229}Th nucleus. Recent data indicates that this transition has the lowest energy of any known nuclear excitation[4], which should make it amenable to study by laser spectroscopy when embedded in a VUV-transparent crystal. Detailed analysis of the crystalline environment leads us to expect that the magnetic dipole-dipole interaction between adjacent nuclei will be the dominant transition broadening mechanism, increasing the transition linewidth from its natural value of $\approx$10 μHz to $\approx$3 Hz. When coupled with the large number of atoms that can be doped into a solid, an improvement in the quantum projection noise limit of as much as 10^6 over current optical clocks may be possible. Furthermore, because of the larger energy scales inherent to nuclear interactions, this transition has $10^3 - 10^5$ times more intrinsic sensitivity to variations in the fundamental constants. The construction of the system appears to be surprisingly easy, as preliminary crystals doped with the (more stable) ^{232}Th isotope have already been produced.

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Trapped Atom Clock on a Chip

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We are developing a compact atomic clock based on the atom chip technology, intended to be a secondary standard. Its frequency reference is the transition between the two magnetically trapped hyperfine sublevels $|F = 1, m_F = -1\rangle$ and $|F = 2, m_F = 1\rangle$ of the ground state of ^{87}Rb. This transition will be interrogated using a two-photon, microwave and RF, Ramsey excitation scheme [1]. The interrogation of trapped atoms has the advantage of long Ramsey times (> 1s), realisable in a compact setup. We will perform the interrogation on a thermal cloud or a BEC, thereby exploring the application of BEC in metrology. Inspired by the proof–of–principle experiment [2] we have constructed a dedicated setup, which is now nearly operational.

The clock stability of the proof-of-principle experiment was 10^{-11} at 1s, limited by trivial technical imperfections, most notably magnetic field noise. Therefore, our new setup includes two layers of magnetic shielding and the detection of both hyperfine states. Furthermore, we have integrated a microwave transmission line on the chip whose evanescent field will couple the interrogation microwave to the atoms. These wires replace the microwave cavity used in fountain clocks. We expect these improvements to earn us a stability in the 10^{-12} at 1s range. Assuming further improvements on the atom number and the cycle time, a stability in the low 10^{-13} at 1s range seems feasible. A clock with this performance would outperform today's best commercial atomic clocks by one order of magnitude, while being much smaller than the atomic fountain primary standards. This combination of features opens a clear perspective for applications like satellite navigation.

Ultimately, the clock stability will be limited by the finite coherence time, which is governed by dephasing between atoms with different trajectories due to the trap-induced shifts. The major frequency shift is the Zeeman shift induced by the trapping field. Its first-order contribution is common-mode for both clock states. Its second order contribution exhibits a minimum at the magic field of 3.23G, where the transition frequency is shifted by 4.5kHz from its zero-field value [3]. However, it is favorable to operate the clock trap slightly below this magic field, in a region where this second order Zeeman shift cancels the collisional shift [4] . We find that in a shallow trap of $(5, 300, 300)$Hz, whose trap bottom is detuned by -0.05G from the magic field, the frequency spread averaged over a cloud of 10^5 atoms and 0.5μK can be as small as 0.17Hz.

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Spin squeezing on the Cs clock transition by QND measurements in a cold atomic ensemble

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We investigate the concept of spin squeezing on the cesium clock transition in a cold and dipole trapped atomic ensemble. The collective atomic state is described in terms of a pseudo-spin, where the z-component represents the population difference between the clock states. The Cs sample is located in one arm of a Mach-Zehnder interferometer and the atomic level population difference is probed non-destructively by measuring the dispersive phase shift of off-resonant light, caused by the state-dependent index of refraction of the atoms. By applying a near-resonant microwave field on the clock transition we can control the evolution of the collective atomic quantum state and steer the pseudo-spin vector on the Bloch sphere. Combining these techniques we are able to prepare the atomic ensemble in a coherent superposition of the clock states and perform QND measurements of the level population difference. The measurement statistics reveal the atomic projection noise. Furthermore, we observe correlations between consecutive measurements on the same atomic sample, indicating that conditional squeezing of the atomic pseudo-spin has be achieved. In that case, the outcome of one measurement can be used to predict the outcome of a subsequent measurement with a precision better than the standard quantum limit.

Reducing Clock Projection Noise with Measurement-Induced Correlations

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For nearly a decade, the best atomic clocks have been limited by atomic shot noise[1], the statistical uncertainty in the result of projecting an ensemble of independent and uncorrelated atoms onto the eigenstates of a measurement. It is possible to go beyond this limit by entangling or correlating the atoms, so that the outcome of a collective measurement is no longer the simple average of independent measurements on each atom[2]. In the Bloch sphere representation, where each (two-level) atom is represented as a spin-$1/2$ and the collective state of an ensemble of N identically-prepared atoms behaves as an angular momentum $S = N/2$, these correlations between atoms correspond to spin squeezing; i.e. to reducing one of the two uncertainty components perpendicular to the mean angular momentum vector below the value of $\sqrt{S/2}$ found in the coherent (uncorrelated) state[3].
Such a squeezed or correlated state can be prepared by projective measurement; for instance by a sensitive measurement of the relative population of the two clock states—corresponding to the z component of the collective spin—of an ensemble of atoms initially prepared in an equal superposition of those two states, i.e. in the xy plane of the Bloch sphere. This requires that the measurement be more precise than the intrinsic $\sqrt{S/2}$ uncertainty of the initial uncorrelated coherent state and that it be non-destructive. The latter requirement means that the magnitude of the effective angular momentum vector, or equivalently the permutation symmetry of the collective atomic state, must not be altered by the measurement. In particular, the measurement must not allow the state of individual atoms to be determined. Practically, this requirement implies the preservation of the clock fringe contrast.
Using a sample of ^{87}Rb atoms confined in an optical resonator (total optical depth ~ 6000) and prepared in a superposition of the two states of the $|F = 1, m = 0\rangle \leftrightarrow |F = 2, m = 0\rangle$ hyperfine clock transition, we have used the atom-induced shift of a cavity resonance to implement such a measurement of relative population. We have reached a sensitivity 7dB below the shot noise limit without a commensurate reduction in fringe contrast, for a net 4dB of squeezing. We have thus created an entangled collective state with reduced fluctuations in one quadrature of the collective spin that may be used to improve the precision of an atomic clock.

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Progress toward Sr Optical Lattice clock at NICT and Vapor Cell Measurement of ^{88}Sr $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_1$ Collision Shifts

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We are building a Sr optical lattice clock at NICT. Our mission is to obtain and deliver the stable frequency standard in Japan and the Sr atomic clock will provide one of the secondary representations of the second. Our latest progress is that we have trapped the ^{88}Sr atoms in a 461 nm Magneto-Optical Trap (blue MOT).
In order to estimate the order of collision shift in $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_0$ clock transition, we measured the collision shifts in the ^{88}Sr $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_1$ transition (λ=689 nm). We performed saturation absorption spectroscopy of thermal atoms in a vapor cell at 455 °C, and the absolute frequency of 689 nm laser was calibrated with a frequency comb which was referenced to International Atomic Time (TAI). This scheme enabled us direct comparison of our cell-based measurement to the accurate frequency obtained with ultracold atoms[1]. We measured the shift due to Sr-Sr binary collisions, as well as collisions with helium, neon and argon buffer gas. The observed shift due to collisions with helium was $\sim$+5 kHz at 10^{-2} Torr. If we assume linear scaling, the shift would be $\delta f/f \sim 10^{-18}$ at 10^{-9} Torr. While our measurement is not directly on $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_0$ clock transition, this measurement may add extra information on the systematic shift of the clock transition at the level of $\delta f/f \sim 10^{-18}$.

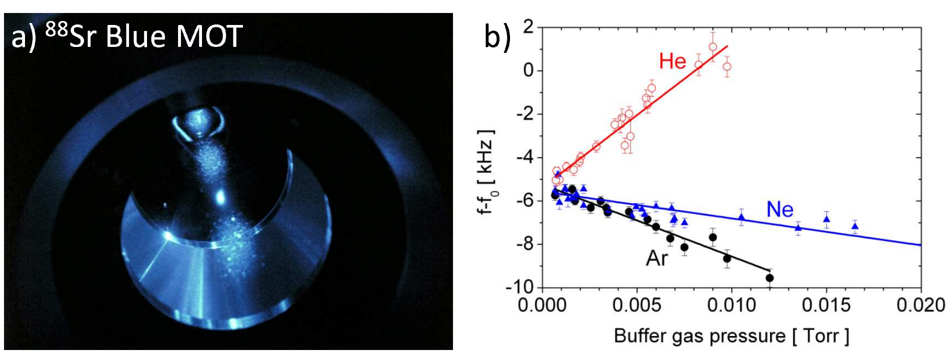

Figure 1: *a) ^{88}Sr trapped in a blue MOT. b) Collision shift dependence on background gas pressure. f_0 is the frequency measured in ref. 1.*

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Optical Lattice Clocks with Single Occupancy Bosons and Spin-Polarized Fermions

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To date, optical clocks based on singly trapped ions and ultracold neutral atoms trapped in the Stark-shift-free optical lattices [1] are regarded as promising candidates for future atomic clocks. So far “optical lattice clocks” have been evaluated with uncertainty of 1×10^{-15} on the basis of the Cs atomic clocks [2]. However, the latter performance is not enough to fully evaluate the former stability as well as accuracy. Therefore, frequency comparison between highly-stable and accurate optical lattice clocks is crucial for this evaluation. Furthermore, one of the essential experimental challenges in the development of optical lattice clocks is to find out the better lattice geometries as well as interrogated atom species [3] (including their quantum statistics) that bring out the potential performance of the clock scheme.

We discuss two possible configurations for optical lattice clocks; three-dimensional (3D) lattice loaded with bosons and one-dimensional (1D) lattice loaded with spin-polarized fermions [4]. In the former scheme, a single occupancy lattice suppresses bunching of bosons and collision shifts. While in the latter scheme, collisional frequency shift is suppressed by the quantum statistical property of identical fermions. This Pauli blocking of collisions, therefore, critically depended on the degree of spin polarization of fermionic atoms, which we carefully investigated in the Rabi excitation process of the clock transition.

We will present frequency comparison of these two optical lattice clocks based on fermionic ^{87}Sr and bosonic ^{88}Sr. By operating these clocks sequentially[5], we achieved the stability 5×10^{-16} after $2,000$ s averaging time. Such measurements will offer an important step to ascertain the lattice clocks’ uncertainty at the 10^{-16} level and beyond, where no working standard exists.

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Laser-cooled atoms coupled to a magnetic micro-cantilever

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Micro-cantilevers have demonstrated remarkable force sensitivity, while dilute atomic gases can exhibit long coherence times and on-chip atomic systems have proven to be useful for quantum control and manipulation. The direct coupling of the spin-degrees of freedom of an atomic vapor to the vibrational motion of a magnetic cantilever tip has recently been demonstrated[1], and prospects for coupling a BEC on an atom-chip to a nano-mechanical resonator have been recently discussed[2]. Possible applications include chip-scale atomic devices, in which localized interactions with magnetic cantilever tips selectively influence or probe atomic spins. As a next step towards the realization of a strongly coupled ultra-cold atom-resonator system, we have constructed an apparatus to study the direct coupling between the spins of an ensemble of laser-cooled Rb atoms and a magnetic tip on a micro-cantilever. The cantilever with magnetic tip is shown in Fig. 1. The atoms will be loaded from a Magneto-Optic-Trap (MOT) into a magnetic quadrupole trap formed by the cantilever tip and external magnetic fields. The cantilever will be driven capacitively at its resonance frequency ($\sim$MHz), resulting in a coherent precession of the trapped atomic spins with a matching Larmor frequency. Such spin precession can be observed by monitoring trap loss through fluorescence or by optical detection of the rotation of the atomic magnetization. Prospects for measuring the back-action of the ensemble of atomic spins on a cantilever beam will also be discussed. Ultimately, if a particular cantilever mode can be cooled to the single-phonon level perhaps in a cryogenic experiment with additional feedback cooling, non-classical states of the atomic degrees of freedom could be transferred to the motional states of the resonators and vice versa, possibly leading to novel tests of quantum mechanics at macroscopic scales.

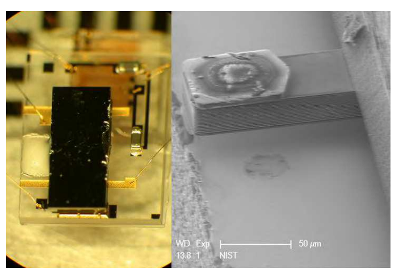

Figure 1: *(left) Optical micrograph of cantilever capacitive drive stack and (right) SEM micrograph of Si cantilever with electroplated CoNiMnP magnet.*

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Microwave Power Measurements Using Rabi Oscillations

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A quantum-based microwave powermeter has been proposed a while ago, and measurements have shown that it could lead to the development of a laboratory standard. [1] [2] [3]

Rabi flopping oscillation is a very common phenomenon. Although it has been studied and used extensively, it is only since the introduction of laser cooling techniques, that it would become possible to use the hyperfine interaction as a tool for the precision measurement of the RF field amplitude (power).

The system uses a standard Magneto-Optical Trap as the source of cold atoms. The cold atoms are simply dropped, and later cross a rectangular waveguide transmission line, where the RF field amplitude is to be measured. The atoms probe the RF field and are later probed by a laser beam.

A short section of rectangular metal waveguide constitutes the vacuum chamber. The top and bottom holes where the atoms cross the guide are equipped with cutoff tubes to prevent RF leakage, and the vacuum windows inside the guide are frequency tuned (6.8 GHz) to prevent any standing wave. The incident RF power through the chamber measured by classical techniques such as thermistor-mount or calorimeter.

In order to compare both classical and atomic standards, we plot the population inversion vs the field amplitude. By fitting the frequency of these (Rabi) oscillations, we find the calibration factor of the powermeter and we can also study its linearity.

The system was designed for low level measurements ie, the dropping distance is low which results in an interaction time of about 15 ms. The obtained resolution is about 0.1 % after 60 Rabi cycles ($\approx$ 2 mW). For this power level, the accuracy is limited by the uncertainty on the interaction time. We deduce the transit time in the the waveguide by measuring the initial position of the MOT. This technique leads to a high uncertainty at a low drop distance and a better technique found for the determination of the interaction time.

The paper describes the apparatus, and the measurement techniques.

[1] D.C. Paulusse, N.L. Rowell and A. Michaud, “Realization of an Atomic Microwave Power Standard.” *Proc. Conference on Precision Electromagnetic Measurements*, 2002, pp. 194-195, online: http://arxiv.org/physics/0504066

[2] T.P. Crowley, E.A. Donley and T.P. Heavner, “Quantum-Based Microwave Power Measurements: Proof-of-concept Experiment.”, in *Rev. Sci. Instrum.* Vol. 75, no, 8 pp. 2575-2580, 2004. DOI: 10.1063/1.1771501

[3] D.C. Paulusse, N.L. Rowell and A. Michaud, “Accuracy of an Atomic Microwave Power Standard.”, *IEEE Trans. Instr. Meas.*, Vol 54. no 2 pp. 692-695. online: http://arxiv.org/physics/0503111

Quantum optics near surfaces

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The main focus of our experiments is the behavior of matter waves which are prepared at a very low distance to a surface. There atom-surface interactions like the Casimir-Polder (**CP**) force play a dominant role.
In our case the surface is the facet of a glass prism. The evanescent wave of a laser beam which is reflected at this facet will allow us to add short range dipole potentials acting on the atoms. A laser beam which is blue-detuned to the D2 line of ^{87}Rb will make a repulsive potential decreasing exponentially with the distance from the surface. This steep potential compensates for the attractive CP-force and thus forms a controllable barrier at a distance of a few hundred nanometers from the surface.

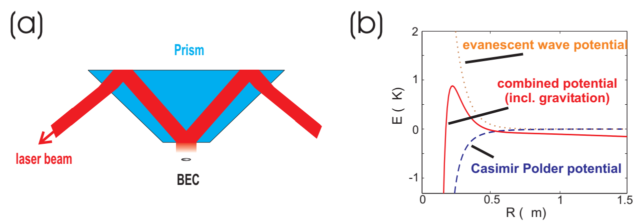

Figure 1: ***(a)*** *Experimental setup: A BEC is placed below the surface of a prism in the evanescent wave of a reflected laser beam* ***(b)*** *Barrier formed by the superposition of CP- and evanescent wave dipole-potential*

Matter-waves propagating towards this barrier may either be reflected or transmitted. The reflectivity of the barrier is determined by its height compared to the kinetic energy of the matter-waves. Measuring the reflectivity as a function of the barrier height will thus allow us to deduce the CP-potential.

A short-time perspective of measurements also includes a nondestructive measurement of the atom number in a Bose Einstein Condensate (**BEC**). A BEC overlapping with the evanescent wave of a far detuned laser beam will shift the phase of the reflected light by an amount of the order of 10^{-4} rad. Monitoring this phase shift as a function of time will provide information about atom number fluctuations in a BEC.

In the long term we plan to tailor nano potentials on the surface by means of surface plasmon polaritons (**SP**). Deposition of metal layers on the prism surface which are structured on the nanometer scale should allow for a local excitation of SPs. The light-induced oscillation of the electrons in these layers strongly enhances the electrical field of the evanescent dipole potential. The implementation of such potentials opens up possible applications in quantum information.

Realization of localized Bohr-like wavepackets

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We present a protocol and its experimental realization for the formation of the original Bohr atomic model,[1] an electron revolving around the nucleus on a (near) circular orbit.
Highly-excited Rydberg atoms in circular states are characterized by extremely high values of one component of the angular momentum $\langle L\rangle \sim \pm(n-1)\hbar$, where n is the principal quantum number. Stationary high-l states have become accessible via laser excitation in external fields.[2] The development of ultrafast electromagnetic pulses[3] opens up the possibility of engineering non-stationary circular wavepackets which resemble a localized quasi-classical electron moving in a Kepler orbit.
Here we experimentally and theoretically demonstrate the creation of such wavepackets near $n \sim 300$ which behave much as a classical electron in a nearly circular Kepler orbit. The motion of the wavepackets can be followed for several Kepler periods and provides a direct analog of the original Bohr atom.[4] Such Bohr-like wavepackets could represent an important stepping stone towards realization of phase-locked correlated planetary configurations in multi-electron atoms.

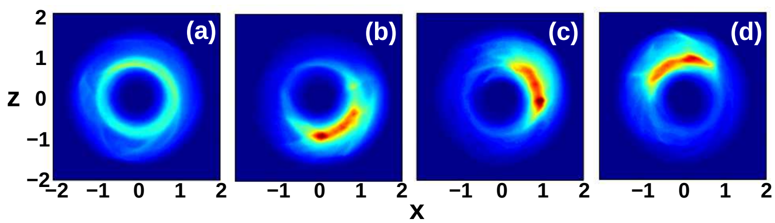

Figure 1: *Circular state (a) and electron wavepacket on Bohr orbit (b-d) in K ($n \sim 300$) after laser excitation and application of a half-cycle pulse.*

[1]N. Bohr, Phil. Mag. 26, 1 (1913)
[2]R.G. Hulet and D. Kleppner, Phys. Rev. A 51, 1430 (1983)
[3]F.B. Dunning, J.C. Lancaster, C.O. Reinhold, S. Yoshida, and J. Burgdörfer, Adv. At. Mol. Opt. Phys., 52 49 (2005)
[4]J.J. Mestayer et al. Phys. Rev. Lett. (2008, in print)

Earth-Field Self Oscillating Magnetometer

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Atomic magnetometers using ultra-narrow resonances based on coherences between Zeeman sublevels in alkali atoms, have been under development since the 1960s . Their high sensitivity makes them a possible alternative to SQUIDS without requiring the use of cryogenic equipment. While recent efforts have been dedicated to working in a magnetically shielded environment where the magnetic field can be tightly controlled, renewed interest in magnetometry in an unshielded environment leads to other challenges because of the fluctuations in the Earth magnetic field [1].

We will present experimental results on the performance of an all-optical self-oscillating atomic magnetometer/gradiometer based on alignment coherences operating at Earth magnetic field in an unshielded environment[2]. Our magnetometer combines amplitude modulated non-linear optical rotation (AM NMOR) and separate pump and probe beams. Its features are high projected sensitivity and wide bandwidth. Potential future applications range from geophysics to biomagnetic measurements in the field, and may serve as the basis of devices used in air- and space-borne platforms.

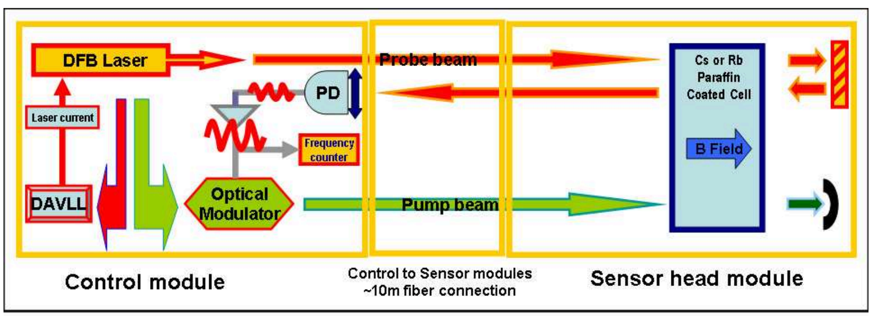

Figure 1: *-Magnetometer configuration (single sensor),*
-DAVLL: Dichroic Atomic Vapor Laser Lock,
-DFB: Distributed Feed Back laser,
-PD: Photo Diodes.

[1]D. Budker, M.V. Romalis, Nature Physics, **Vol. 3, p.227-334, April 2007**
[2]J.M. Higbie, E Corsini and D Budker, Rev. Sci. Instrum. **77, 113106 (2006)**

High-duty cycle magnetometry with cold atoms in dark optical tweezers

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Dark optical traps for cold atoms are useful for precision measurements because they provide deep potentials with reduced perturbations and low trap laser power requirements. We have used blue-detuned, high charge number hollow laser beams to confine ^{87}Rb for magnetometry and Faraday spectroscopy. The hollow laser beams are crossed in a bowtie configuration, forming a deep (300μK), large volume (0.1mm^3), box-like potential using only 200mW of laser power detuned 0.2 nm from resonance.

Magnetic field measurements are made by optically pumping the atom sample to a stretched magnetic sublevel. The subsequent Larmor spin precession, proportional to the magnetic field strength, is monitored by measuring the magneto-optic polarization rotation of a linearly polarized probe beam. The trap is sufficiently deep to make several hundred measurements of the magnetic field without reloading the trap (Fig. 1). Such measurements provide a real-time monitor of the magnetic field. We have used the precession signals to measure and compensate time-varying magnetic fields to within 10 nT over a 400 ms time window[1]. We discuss optical properties of the traps and limits to the interrogation time.

By dynamically scanning the crossed hollow beams[2], we can quickly sample the magnetic field over an extended length. We discuss our work to make multiple measurements over several millimeters in a single loading cycle to provide both high spatial and temporal resolution of the magnetic field.

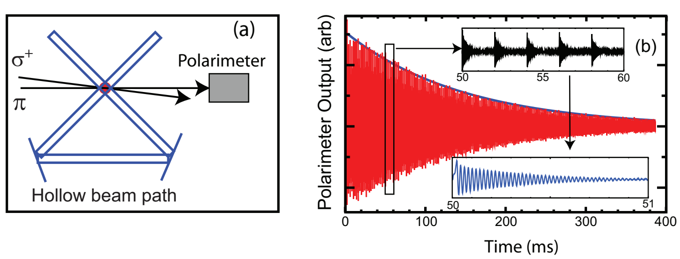

Figure 1: *a) Hollow beam layout. b) Larmor precession signals over 400 ms at a 500 Hz sampling rate. Figures adapted from Ref. 1.*

[1] M. L. Terraciano, M. Bashkansky, and F. K. Fatemi, Phys. Rev. A **77** 063417 (2008)
[2] F. K. Fatemi, M. Bashkansky, and Z. Dutton, Opt. Express **15**, 3589 (2007)

Magneto-optical Resonances in Atomic Rubidium in Ordinary and Extremely Thin Cells

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We present the results of an experimental and theoretical investigation of nonlinear magneto-optical resonances in atomic rubidium in an extremely thin vapor cells (ETCs) and an ordinary cell. Magneto-optical resonances can be bright or dark, depending on which hyperfine transition is excited. Although these sub-natural linewidth resonances have been known for some time [1], recent studies have shown that their characteristics can change in dramatic ways in ETCs. For example, it was reported that the Cs $6S_{1/2}$ $F_g = 3 \rightarrow F_g = 4$ transition appears dark in an ETC, even though it is bright in an ordinary vapor cell [2]. ETCs have the useful property that they allow sub-Doppler spectroscopy [3]. Thus, hyperfine transitions that are unresolved in ordinary cells can be resolved in ETCs. One would therefore expect that magneto-optical resonances would be easier to interpret in ETCs. However, it appears that new effects have to be taken into account. It has been suggested that collisions with the walls of the ETC depolarize the excited state and thus change the course of the optical pumping processes that lead to bright or dark resonances [3]. To test such theories and to further understand how Doppler broadening, relaxation time, and other effects influence the shape and contrast of the resonances, we compare results from ETCs with those from ordinary cells and from detailed calculations. In our experiment, we use Rubidium vapor in an ETC of thickness L between 150 nm and 1600 nm. The polarization of the exciting laser radiation is perpendicular to the magnetic field, which was scanned, and the fluorescence is observed in the direction along the magnetic field. In order to test how well our model can describe ETC behavior, we study resonances at different laser powers, beam diameters, and wall separations L in both an ETC and an ordinary cell. The experimental results are compared to theoretical calculations based on the optical Bloch equations, which have proven to be well suited to describe the signals obtained in ordinary vapor cells [4]. By requiring the model to take into account a variety of different parameters, it will be possible to understand any new effects that should be taken into account when modelling magneto-optical resonances in ETCs.

We acknowledge support from the Latvian National Research Programme in Material Sciences Grant No. 1-23/50, the University of Latvia grant Y2-ZP04-100, the ERAF grant VPD1/ERAF/CFLA/05/APK/2.5.1./000035/018, and the INTAS projects 06-1000017-9001 and 06-1000024-9075. A. J., F. G., and L. K. acknowledge support from the ESF project.

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[2] C. Andreeva et al. Phys. Rev. A 76 063804 (2007)
[3] D. Sarkisyan et al., Opt. Commun. 200, 201 (2001)
[4] M. Auzinsh et al. arXiv:0803.0201v1 [physics.atom-ph]

Error estimation for the generalized Dykhne-Davis-Pechukas approach

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This work presents an analytic results related to the Dykhne-Davis-Pechukas approach in the case of more than one transition points situated on different Stokes lines. Davis and Pechukas [1] have suggested a generalization to include the contributions from all zero points lying on the lowest Stokes line (the closest one to the real axis) in a coherent sum. This suggestion was later verified by Joye [2]. Although not rigorously proved, Suominen [3] has shown that for the Demkov- Kunike models the full summation, involving infinitely many transition points, leads to the exact result as for the Landau-Zener model. We present a rigorous result for the full summation of all transition points. According to the geometry of the Stokes lines, we show that the generalized Dykhne-Davis-Pechukas approach provides correct asymptotic probability for nonadiabatic transitions even when there are some singularities of the quasienergy splitting, as for the Rosen-Zener model.

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Controlling ultracold Rydberg atoms in the quantum regime

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The large size of Rydberg atoms affects their coupling to the inhomogeneous magnetic field of a common Ioffe-Pritchard trap and necessitates a two-body treatment. An analysis of the fully quantized center of mass and electronic states reveals that very tight confinement of the center of mass motion in two dimensions is achievable while barely changing the electronic structure compared to the field free case. [1] This provides a prerequisite for generating a one-dimensional ultracold Rydberg gas. [2]

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[2]M. Mayle, B. Hezel, I. Lesanovsky and P. Schmelcher, Phys. Rev. Lett. **99**, 113004 (2007)

F-Resolved Magneto-optical Resonances in Atomic Cesium at D1 Excitation

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We present the results of a detailed experimental and theoretical investigation of bright and dark nonlinear magneto-optical resonances at D1 excitation of atomic cesium in an ordinary vapor cell. Although these effects have been known for some time [1], discrepancies continued to exist between theoretically predicted [2] and experimentally observed [3] behavior. One reason was that, because of Doppler broadening, several hyperfine levels contributed simultaneously to the signals in the systems that were studied previously. To clarify the discrepancies in the literature, a system in which each hyperfine transition could be studied separately was desirable. The Cesium D1 line met this requirement because the separation between the different hyperfine levels exceeds the Doppler width. At the same time, in an ordinary vapor cell, these magneto-optical resonances have widths that are less than the natural linewidth.

In our experiment, cesium atoms were excited by linearly polarized laser radiation with its polarization vector perpendicular to the magnetic field, which was scanned across zero. Laser induced fluorescence was observed along the magnetic field direction. Resonances appeared at zero magnetic field. Signals were obtained for various beam diameters, which are related to transit relaxation time, and laser power densities. The experimentally obtained signals were compared to the results of a theoretical calculation based on the optical Bloch equations, which averaged over the Doppler contour of the absorption line and accounted for the contribution of all hyperfine levels as well as mixing of magnetic sublevels in an external magnetic field. Agreement between experiment and theory was excellent and supported the traditional theoretical interpretation, which attributed these effects to optical pumping and to the relative strengths of transition probabilities between different magnetic sublevels in a given hyperfine transition. This theoretical model is now being applied to understand these effects in Extremely Thin Cells [4] of nanometric dimensions, which are interesting because they allow sub-Doppler spectroscopy and thus make it possible to study more closely spaced hyperfine transitions individually.

This work was supported in part by the Latvian National Research Programme in Material Sciences Grant No. 1-23/50, the University of Latvia grant Y2-ZP04-100, the ERAF grant VPD1/ERAF/CFLA/05/APK/2.5.1./000035/018, and the INTAS projects 06-1000017-9001 and 06-1000024-9075. A. J., F. G., and L. K. acknowledge support from the ESF project.

[1] J.-C. Lehmann and C. Cohen-Tannoudji, Comptes Rendus de l'Acadmie des sciences (Paris) 258, 4463-4466 (1964) and G. Alzetta, A. Gozzini, L. Moi, and G. Orriols, Il Nuovo Cimento B 36, 5 (1976)

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[4] D. Sarkisyan et al., Opt. Commun. 200, 201 (2001)

Outcoupling of Cold Atoms by Finite-line-width Radio Frequency Field

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By use of an rf-field it is possible to couple different Zeeman sublevels of an atomic gas sample. In an inhomogeneous magnetic field only certain sublevels are trapped. Therefore, atoms which are driven by a weak outcoupling field from a trapped into an untrapped $M_F = 0$ state fall freely under gravity. This coherent beam of atoms emitted from the source of cold trapped atomic cloud is referred to as atom laser[1]. Using simultaneously multiple different rf-frequencies one can create a set of atomic beams originating from spatially different resonance points. Because of the coherence properties, these beams interfere with each other, which can be observed as a beat mode in the density amplitude[2].

We present a simple yet realistic model for such outcoupling scenario using wave packet techniques arising from a finite line width of the coupling. Furthermore, our approach gives a natural interpretation for the classically intuitive event of free fall of atoms, while being consistent with the quantum mechanical description.

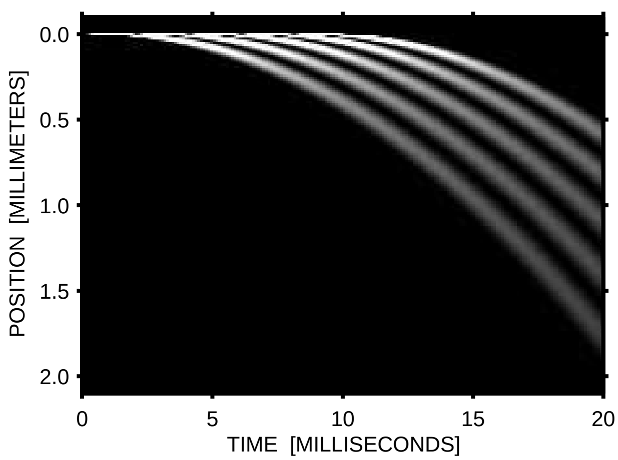

Figure 1: *Analytical wave packet result for the density profile of two interfering atomic beams outcoupled from a trap at the origin. Frequency difference of the coupling pulses is 500 Hz, and the pulse duration is 10 ms.*

[1] I. Bloch, T. W. Hänsch, and T. Esslinger, Atom Laser with a cw Output Coupler, Phys. Rev. Lett. **82**, 3008 (1999).

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Fractional resonances of the δ-kicked accelerator

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We consider the resonant dynamics in a dilute atomic gas, falling under gravity through a periodically pulsed, standing-wave laser field. This atom-optical realisation of the quantum δ-kicked accelerator generalises our study into the effect of temperature upon quantum resonance and antiresonance[1]. Modifying the laser potential to a walking-wave allows the acceleration experienced by the atoms to be tuned. We observe fractional resonances, with the temperature dependence shown in Figs. 1(a)–(c). We explore the transition between temperature extremes by investigating the evolution of the individual quasimomentum eigenstates [Fig. 1(d)]. Changing the acceleration reveals a rich structure of resonant phenomena [Fig. 1(e)][2].

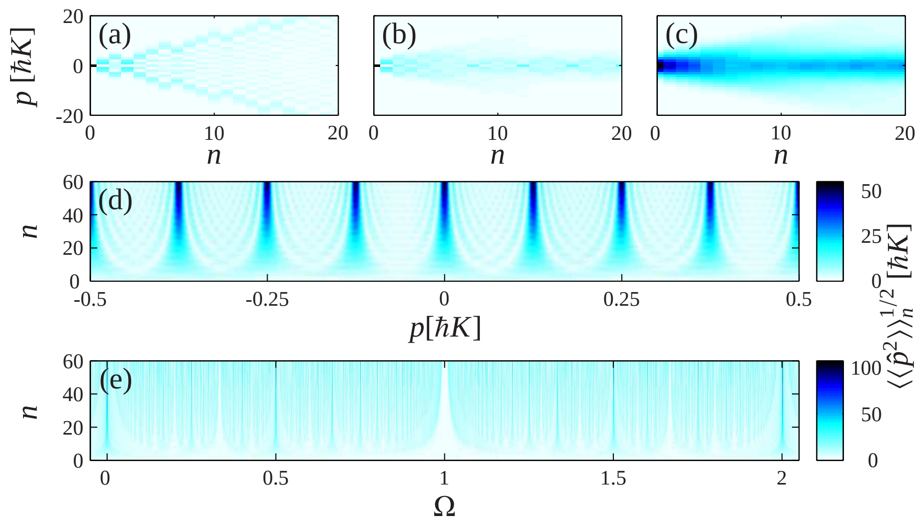

Figure 1: *The atom-optical δ-kicked accelerator, for an atom cloud with initial momentum distribution of standard deviation $w\,\hbar K$: (a) in the ultra-cold limit ($w = 2^{-10}$); (b) at an intermediate temperature ($w = 2^{-3}$); (c) in the thermal limit ($w = 2.5$), for a fourth-order resonance (setting effective acceleration parameter, $\Omega = 1/4$). The distributions are analysed by their standard deviation: (d) over the quasimomentum range, for $\Omega = 1/4$; and (e) over Ω for the $|p = 0\rangle$ subspace. Gravitational acceleration is incorporated into Ω.*

[1]Saunders, Halkyard, Challis and Gardiner, *Phys. Rev. A* **76** 043415 (2007)
[2]Saunders, Halkyard, Challis and Gardiner, *in progress* (July 2008)

One-Dimensional Rydberg Gas in a Magnetoelectric Trap

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We discuss the quantum properties of ultracold Rydberg atoms in a magnetic Ioffe-Pritchard trap which is superimposed by a homogeneous electric field. The magnetic Ioffe-Pritchard trap as the basic ingredient of our setup allows very tight confinement of the center of mass motion in two dimensions while the electronic structure is barely changed compared to the field free case [1] [2]. This paves the way for generating a one-dimensional ultracold Rydberg gas by superimposing the magnetic Ioffe-Pritchard trap with an additional homogeneous electric field: Tightly trapped Rydberg atoms can thus be created in long-lived electronic states exhibiting a permanent electric dipole moment of several hundred Debye. The resulting dipole-dipole interaction in conjunction with the radial confinement is then demonstrated to give rise to an effectively one-dimensional ultracold Rydberg gas with a macroscopic interparticle distance[3]. Moreover, analytical expressions for the electric dipole moment and the required linear density of Rydberg atoms are derived.

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Optical field Induced Faraday Rotation at Geophysical Magnetic fields: Role of Electromagnetically Induced Transparency

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In recent years there has been a significant interest in the study of electromagnetically induced transparency (EIT) in the presence of relatively high magnetic fields (~50G) and optical field induced Faraday rotation[1 2 3]. We examine the coexistence of EIT and Faraday rotation at geophysical magnetic fields. In the present paper, we report optical field induced Faraday rotation in ^{85}Rb and ^{87}Rb D_2 lines by realizing a system. Weak probe and strong coupling fields have been derived from two external cavity diode lasers. The measurements were performed using paraffin coated and uncoated rubidium vapour cells at room temperature. An analysis of the line shapes observed in the experiments done with paraffin coated, and uncoated, vapour cells has enabled us to assess the importance of ground state coherence. The Doppler- broadened line shape is analysed as a function of probe laser detuning for different magnetic fields. The line shape changes drastically when a magnetic field of the order of a few mG is applied, which is due to the effect of EIT on Faraday rotation.

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A multichannel second-order gradiometer for cardiomagnetic field imaging

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We present the status of our optical multichannel magnetometer used to map the beating human heart. Although SQUID-based devices already make such measurements in a few medical centers worldwide, the search for a new measurement method is motivated by the high cost of the LHe cooling SQUIDs require. In our atomic Cs magnetometers, a signal indicating the local magnetic field is generated by the combined interaction of resonant optical pumping (using circularly polarized D_1 light) and magnetic resonance among the 6S $F{=}4$ Zeeman levels. Cs vapor is confined in a room-temperature, evacuated, 30 mm diameter paraffin-coated Pyrex cell, produced by us. Intrinsic cell sensitivities are individually measured and are in the range 10–25 fT$/\sqrt{\text{Hz}}$. A compact array of cells allows multichannel heart field measurements with spatial resolution of 50 mm.
The optical magnetometer array operates in an Al shielded environment, with earth-field cancellation coils, however, the measurement performance is limited by external magnetic noise. A second-order gradiometer arrangement permits direct feedback compensating linear gradient variations of the external field. Currently, fully digital FPGA (Field Programmable Gate Array) electronics drive an eight-sensor array, with six measurement channels and two reference sensors for the second-order gradiometer. We can map a 30×40 cm area (36 points) above the chest in 15 minutes, a time much shorter compared to our first apparatus[1]. Figure 1 shows typical signals (80 trace average) detected by three sensors located above the chest of a healthy adult.

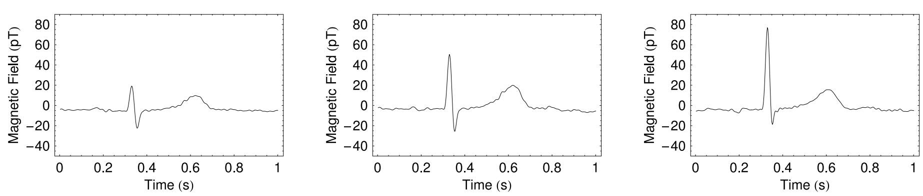

Figure 1: *Simultaneously recorded human magnetocardiogram signals measured at 50 mm separation using second-order gradiometers.*

By the end of 2008, we will operate a 25-channel second-order gradiometer array whose 19 simultaneous measurement channels will be able to reduce the acquisition time for a full heart map to only a few minutes. This optical magnetometer technology promises to be more affordable for hospitals, and hence of interest for diagnosing heart disease.
Funded by the Velux Foundation, and the Swiss National Science Foundation.

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Nonlinear Faraday Effect for magnetometric applications

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Modern optical magnetometers reach the sensitivity comparable with, or even exceeding that of SQUIDs and find many spectacular applications[1]. Nonlinear Faraday Effect (NFE) is one of the magneto-optical phenomena that find its use in sensitive magnetometry. It is based on light-intensity-dependent rotation of the polarization plane of linearly polarized light propagating through a medium placed in a magnetic field. The rotation results from light-induced long-lived quantum superpositions of Zeeman sublevels of atomic ground state. Under special conditions, ultra-narrow resonances ($\sim 10^{-11}$ T) are observed. The resonances allow measuring very weak magnetic fields with the sensitivity reaching 10^{-15} T/Hz$^{1/2}$ [2].

We report on our approach to optical magnetometry based on NFE aiming at extending the dynamic range without compromising on high sensitivity. Application of light intensity modulation leads to appearance of additional resonances at much stronger fields (Fig.1a). The extra resonances have their positions strictly determined by the modulation frequency and hence they can be shifted to the fields of desired values. This significantly expands the range of our magnetometer which is now bigger than those of other optical magnetometers. With the field-tracking algorithm, we demonstrate the ability of tracking static or slowly varying magnetic fields in a wide range (see Fig.1b). With the non-optimized setup we show sensitivity of about 4×10^{-13} T/Hz$^{1/2}$ in a dynamic range of about 7.5×10^{-6} T [3]. We also discuss prospects of the technique for practical applications.

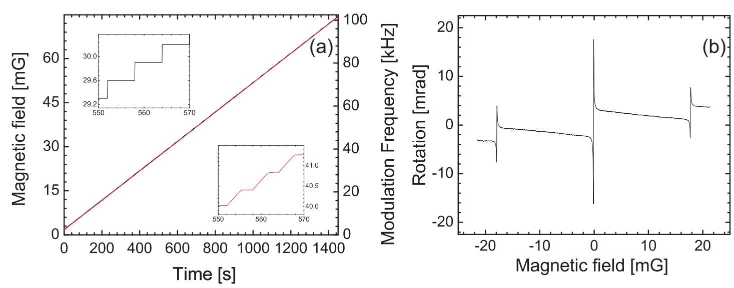

Figure 1: *(a) Signals of NFE with amplitude-modulated light. (b) Tracking of magnetic field with the NFE magnetometer. Every 9 s magnetic field was increased by 15×10^{-9} T. The inset blowout the magnetic field steps and the resulting frequency response.*

[1] D. Budker, M. V. Romalis, Nat. Phys. **3**, 227 (2007).

[2] D. Budker, D.F. Kimball, S.M. Rochester, V.V. Yashchuk, and M. Zolotorev, Sensitive Magnetometry based on Nonlinear Magneto-Optical Rotation, Phys. Rev. A **62**, 043403 (2000).

[3] S. Pustelny, A. Wojciechowski, M. Gring, M. Kotyrba, J. Zachorowski, W. Gawlik, J. Appl. Phys. **103**, 063108 (2008).

Precision Computation of High Resoloving Spectrum Near Ionization Threshold

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A new method is proposed to describe quantum dynamical processes in finite space by using of a set of discretized complete basis. In this method, the finite space complete basis were obtained by solving self-consistent field equation with reflecting boundary conditions. Such method can be used in systems with non-separable Hamiltonians, eg. atoms in strong magnetic field, and time dependent dynamical problems, eg. atoms in high intensity laser field. To illustrate the validity of the method, we will present in the poster two examples: the theoretical calculation of high excited states spectrums including continuum of Barium and Sodium.

We have calculated the spectrum of high excited states including continuum for Barium from $6s^2$ to $6snp/6s\varepsilon p$ channel. In order to achieve the experimental resolution[1], ie. 0.3cm^{-1}(FWHM), we choose a large space size of 25000 bohr. The calculated optical oscillator strength is folded with a normalized Gaussian function with the experimental line width. As shown in Fig. 1, our calculated result has the same features as experimental one[1]. The measured oscillator strength converges to oscillator strength densities near the threshold and extends smoothly to continuum region.

We have also calculated a complete spectrum of optical oscillator strength densities of Sodium for dipole transitions from $3s$ state to final states of p channel, including infinite Rydberg series and adjacent continuum states. As shown in Fig. 2, the calculated result is in agreement with experimental results[2,3] below the well known Cooper-minima. The position of the Cooper-minima is in good agreement with experimental results. The difference between the experimental and theoretical result above the Cooper-minima has been discussed in detail in our earlier works[4,5].

As a summary, we can use the finite space complete basis method to do precision computation of the high excited states spectrums including continuum. Further more, using the same basis, we can solve the magnetic field problems by adding the diamagnetic matrix elements. We can also generate the Green's function of the systems using this basis to solve time dependent dynamical problems.

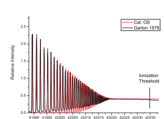

Fig. 1

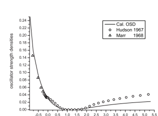

Fig. 2

[1]K. T. Lu., F. S. Tomkins. and W. R. S. Garton., Proc. R. Soc. A.362, 421(1978).
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Efficient broadband de-excitation of Rydberg atoms with half-cycle pulses

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We report on progress towards demonstrating population redistribution of Rydberg atoms using a train of unipolar terahertz bandwidth pulses (half-cycle pulses) as initially proposed by Hu and Collins[1]. In principle this broadband technique should allow for the efficient de-excitation of antihydrogen atoms from the currently produced mix of excited states to the ground state which is a necessary prerequisite for a CPT comparison with hydrogen[2].

To produce a train of unipolar pulses with pulse widths shorter than the 10 ps orbit period of an atom in $n \approx 40$ and with a repetition rate allowing for many pulses within the lifetime of an optically excited atom ($\tau \approx 75\mu\mathrm{s}$), we have developed and characterized a system based on GaAs photoconductive switches pumped by a femtosecond oscillator. In this technique, the GaAs wafer is biased using aluminum electrodes produced using photolithography. When carriers in the wafer are then excited by the femtosecond pulse they are accelerated by the electric field and radiate a short pulse. Due to the asymmetry between excitation by a short pulse and the long carrier lifetime of semi-insulation GaAs, the radiated field is primarily unipolar. For the final experiment, a cloud of ultracold $^{85}\mathrm{Rb}$ atoms are then excited to a Rydberg state, allowed to interact with the 80 MHz pulse train of half-cycle pulses, and the final state distribution is measured as a function of the pulse train parameters.

Initial demonstrations of the techniques used for the generation of half-cycle pulses and Rydberg atom production will be described. We will also report on further developments of novel techniques utilizing the unipolar magnetic field of the half-cycle pulse. These are useful both for probing magnetic systems as well as for terahertz radiation detectors.

[1] S. X. Hu and L. A. Collins, "Redistributing populations of Rydberg atoms with half-cycle pulses," *Phys. Rev. A* **69**, 041402 (2004).

[2] G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, et al., "Driven Production of Cold Antihydrogen and the First Measured Distribution of Antihydrogen States," *Physical Review Letters* **89**, 233401 (2002).

Magnetic interactions of cold atoms with anisotropic conductors

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We analyze atom-surface magnetic interactions on atom chips where the magnetic trapping potentials are produced by current carrying wires made of electrically anisotropic materials. We discuss a theory for time dependent fluctuations of the magnetic potential, arising from thermal noise originating from the surface. It is shown that using materials with a large electrical anisotropy results in a considerable reduction of heating and decoherence rates of ultra-cold atoms trapped near the surface, of up to several orders of magnitde. The trap loss rate due to spin flips is expected to be significantly reduced upon cooling the surface to low temperatures. In addition, the electrical anisotropy significantly suppresses the amplitude of static spatial potential corrugations due to current scattering within imperfect wires. Also the shape of the corrugation pattern depends on the electrical anisotropy: the preferred angle of the scattered current wave fronts can be varied over a wide range. Materials, fabrication, and experimental issues are discussed, and specific candidate materials are suggested.

Level-crossing transition between mixed states

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The Landau-Zener model[1,2] is conventionally used for estimating transition probabilities in the presence of crossing levels. Nevertheless, because of the infinite duration of the coupling in this model, the propagator involves a divergent phase. It has been shown that this phase causes undefined populations in the degenerate Landau-Zener model[3]. In this work we show that even in the original Landau-Zener model we have undefined populations when we deal with pure superposition states or with mixed states. We show that the Allen-Eberly model[4] can be used as an alternative to the Landau-Zener model to describe the dynamics of such level-crossing problems[5].

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Dark dynamic acousto-optic ring lattices for cold atoms

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We propose a straightforward method for the generation of dynamic dark optical ring lattices, without requiring Laguerre-Gauss beams, spatial light modulators, large optical coherence lengths or interferometric stability. Simple control signals allow these lattices to be reproducibly rotated about the beam axis and spatially modulated, offering manifold possibilities for the creation of complex dynamic lattices. We demonstrate the optical realization of these ring lattices as rastered 2D intensity distributions from a single laser beam, which, in conjunction with a magnetic trap, will enable precision trapping and manipulation of ultracold species using blue-detuned light. The technique is ideal for azimuthal ratchet, Mott insulator and persistent current experiments with quantum degenerate gases. We compare and contrast our scheme to other related techniques.[1] [2]

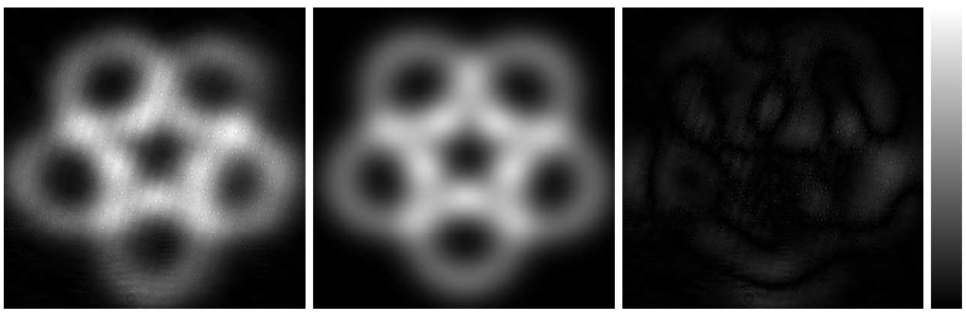

Figure 1: *Experimental relative intensity distribution (area* $\approx (4\,mm)^2$*, exposure 1ms), corresponding least-squares theoretical fit and fit residue. See Ref.* [3] *for optical lattice movies comparing experimental and theoretical rotation and amplitude modulation.*

[1] S. Franke-Arnold et al., Opt. Express **15**, 8619 (2007).
[2] S. K. Schnelle *et al.*, Opt. Express **16**, 1405 (2008).
[3] www.photonics.phys.strath.ac.uk/AtomOptics/AOFerris.html

Non-equilibrium quantum dynamics of bosonic atoms in an optical lattice

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We study the effect of quantum and thermal fluctuations on bosonic atom dynamics in optical lattices within the truncated Wigner approximation in a shallow, strongly confined 1D optical lattice. This provides means to investigate the validity of the classical Gross-Pitaevskii equation in optical lattices. We study the loss of the phase coherence of atoms along the lattice, and the reduced atom number fluctuations in individual lattice sites. We also address dynamical quantum state preparation methods in such systems.

Coherent delocalization of matter waves in driven lattice potentials: a new tool to engineer quantum transport over macroscopic distances

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We present the first experimental demonstration of the Wannier-Stark intraband transitions and their application to the control of quantum transport in lattice potentials. Atomic wave packets loaded into a phase-modulated vertical optical-lattice potential exhibit a coherent delocalization dynamics arising from intraband transitions among Wannier-Stark levels. Wannier-Stark intraband transitions are here observed by monitoring the in situ wave-packet extent. By varying the modulation frequency, we find resonances at integer multiples of the Bloch frequency and the resonances show a Fourier-limited width for interrogation times up to 15 s[1] (left figure). Under non-resonant driving of the lattice phase we coherently control the spatial extent of the wavefunction by reversibly stretching and shrinking the wavefunction over a millimeter distance[2] (right figure). The remarkable experimental simplicity of the scheme would ease applications in the field of quantum transport and quantum computing. We also found that the resonant tunneling process at the basis of the Wannier-Stark intraband transitions can be used to determine the gravity acceleration with sub-ppm sensitivity and sub-millimeter spatial resolution.

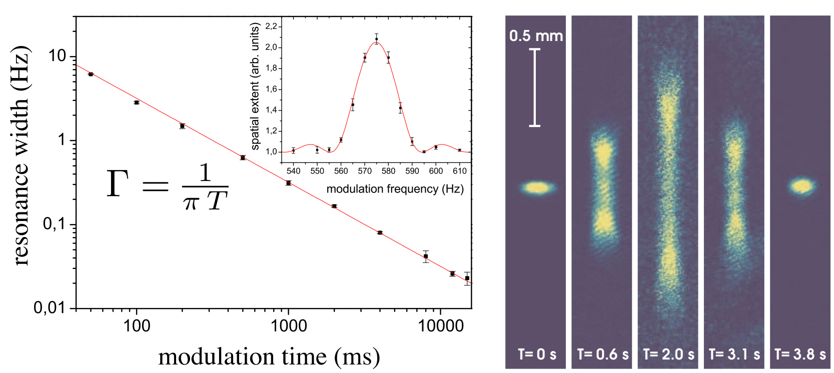

Figure 1: *Left: resonance width* Γ *(see also inset) VS the modulation time T. The line corresponds to the expected Fourier limit. Right: reversible stretching of the atomic distribution under non-resonant driving*

[1] "Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials" V. V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, Phys. Rev. Lett. 100, 043602 (2008).

[2] "Engineering the quantum transport of atomic wavefunctions over macroscopic distances" A. Alberti, V. V. Ivanov, G. M. Tino, G. Ferrari, arXiv:0803.4069v1 [quant-ph].

Coherent Dynamics of BECs in Periodically Driven Optical Lattice

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In recent years, Bose-Einstein Condensates (BECs) of ultra-cold Gases have become a versatile tool for studying many-body systems. Starting from the simple system of interacting particles in a trap, different techniques can be used to modify the system's Hamiltonian, for example by adding an optical lattice or a magnetic field.
In recent works [1] the possibility of using *d*ynamic rather than static control of the dynamics of a BEC inside an optical lattice has been demonstrated. By periodically shifting back and forth the position of an optical lattice, it is possible to coherently control the external degrees of freedom of the BEC, leading to a change in the inter-site tunneling probability. In the Bose-Hubbard model, the general Hamiltonian H can be written in terms of the on-site energy U and the tunneling rate J. The effect of the shaking is a renormalization of J depending on the strength K and the frequency ω of the driving,

$$\hat{H} = +\frac{U}{2}\sum_j \hat{n}_j\left(\hat{n}_j - 1\right) - J_{eff}\sum_{\langle i,j\rangle}\left(\hat{c}_i^\dagger\hat{c}_j + \hat{c}_j^\dagger\hat{c}_i\right),$$

with $J_{eff} = \mathcal{J}_0(K/\omega)J$ and $\mathcal{J}_0$ is the zero-th order Bessel Function [2].
This renormalization of J adds an additional degree of control over the system, but the complexity of the resulting (quasi-)energy spectrum of the shaken system also introduces difficulties and limits to how the system can be adiabatically prepared and coherently controlled under these circumstances. Here we present our latest experimental results regarding the coherent control and adiabatic preparation in different configurations and dimensionalities with a view to the the possibility of realizing the superfluid-Mott insulator phase transition in the driven system.

[1] H. Lignier et al, *Dynamical Control of Matter-Wave Tunneling in Periodic Potentials*, Phys. Rev. Lett. 99, 220403 (2007)
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Coherence modulation at quantum resonances of δ-kicked rotor

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In recent experiments[1] we have demonstrated coherence preservation for an external state atom interferometer[2] interacting with periodic kicks delivered by an optical lattice potential. This coherence preservation manifests itself in high contrast peaks in the interferometer signal that occur when the kicking period corresponds to the quantum resonances of a quantum kicked rotor[3]. The observed resonances are accompanied by fringes on a finer time scale. The typical signal vs the normalized kicking period τ in the vicinity of quantum resonance ($\tau = \pi$) is shown in Fig. 1.

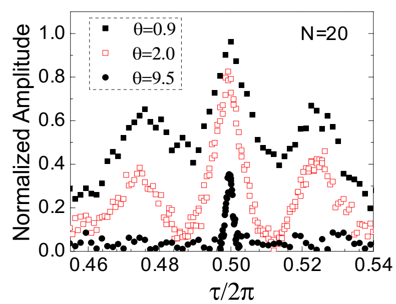

Figure 1: *Fringes at the quantum resonance (initial phase shift is 2π).*

We analyzed these fringes for high pulse areas ($\theta \sim 10$) and quasi-random perturbation regimes. We distinguish two cases depending on the initial conditions at the start of the kicks. If the delay between the interferometer pulse and first kick corresponds to π or 2π phase shifts then the fringes have a maximum at the exact quantum resonances independent of the perturbation strength θ, on the other hand, if the delay corresponds to a $\pi/2$ phase shift, fringes have local minimum at the resonance and its height depends on the perturbation strength θ. In the latter case the amplitude of the "dip" vs the number of kicks N resembles the theoretically predicted "fidelity freeze".
Our observations show an unambiguous manifestation of the interferometric nature of quantum resonances seen in previous quantum kicked rotor implementations[4]. The resonance nature and sensitivity of the observed fringes to the external potentials provides a sensitive tool for precision measurement of recoil frequency and gravity.

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Andreev-like reflections and metastable many-body states with cold atoms in optical lattices

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Cold atoms in optical lattices offer clean realisations of many microscopic lattice models, with excellent control over the system parameters and a variety of techniques to measure the properties of the system. In addition, they exhibit only weak dissipative processes, resulting in long coherence times. This will allow new aspects of time-dependent coherent many-body dynamics to be probed in an experiment. Here we present two examples of how different aspects of many-body dynamics could be probed in these systems.

The first concerns making connections to phenomena predicted but not observed in mesoscopic transport systems, via observation of the propagation of an excitation through the system. We specifically look at Andreev-like reflections, or reflections of negative-density waves, which are predicted to occur in mesoscopic transport systems at boundaries where conductors with different interaction characteristics are connected (e.g., a quantum wire connected to leads). We propose a setup in which such reflections could be observed time-dependently with cold atoms in a 1D optical lattice, with a boundary engineered at which the interaction strength changes [1]. Using time-dependent DMRG methods, we calculate the transport of a density excitation with the context of the Bose-Hubbard model. We compare the resulting reflections with predictions from Luttinger liquid models, and observe strong Andreev-like reflections in experimentally attainable regimes.

In the second we investigate the formation of long lived many-body metastable states and the investigation of related quantum phases. In particular, we address systems of Atomic Lattice Excitons [2], bound metastable particle-hole pairs that are analogues of excitons in semiconductor systems, but make use of the fact that cold atoms in optical lattices provide a cleaner representation of the underlying microscopic models. Such a system would not only make it possible to observe superfluid properties of an system of excitons, but also exhibit a crystalline phase, which arises due to the large difference in tunnelling rates between atoms in different bands of an optical lattice.

[1] A. J. Daley, P. Zoller, and B. Trauzettel, Phys. Rev. Lett. **100**, 110404 (2008).
[2] A. Kantian, A. J. Daley, P. Törmä, and P. Zoller, New J. Phys **9**, 407 (2007).

Bragg spectroscopy of cold atom gases in optical lattices

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The dynamic structure factor $S(\mathbf{q}, \omega)$ provides an important characterization of the dynamic behaviour of quantum many-body systems. In the case of gaseous Bose-Einstein condensates it provides information both on collective excitations (at low momentum transfer **q**) and on the momentum distribution (at high momentum transfer **q**) where the response is single-particle like, thus fully characterizing the excitations of the system. Bragg spectroscopy of cold atomic gases, which consists in coupling two momentum states of the same ground state by a stimulated two-photons transition, gives such a measurement of $S(\mathbf{q}, \omega)$.

The use of optical lattices with cold atomic gases has proven to be a very useful tool in the past years. It allows to change the dimensionality of these systems and study the transition from a superfluid in the presence of a lattice, where the Bloch band picture applies, to a strongly-correlated insulating state, the Mott phase. We are interested in characterizing Bose-Einstein condensates loaded in optical lattices via the measurement of their dynamic structure factor by means of Bragg spectroscopy.

We first have studied the Bragg spectra of 3D and 1D Bose-Einstein condensates in the presence of an optical lattice along the direction of the counter-propagating Bragg beams. From the measurements, we extract the resonance frequency, the width and the transition strength of the transitions to different Bloch bands of the optical lattice. We have also measured the spectra of 1D gases for different trap anisotropies, *i.e.* different Luttinger parameters. In particular, we observe an enlargement of the width of those spectra when the anisotropy increases which could be a signature of the presence of correlations.

Towards Studying Quantum Spin Systems with Ultracold Bosons in an Optical Lattice

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[2]*Present address: Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland*

We present our progress towards the experimental study of quantum spin systems using ultracold bosonic atoms in an optical lattice. In the limit of weak hopping, the two-component Bose-Hubbard model can be mapped to an effective spin-$\frac{1}{2}$ XXZ Heisenberg model[1,2], which can be realized, for example, by atoms of a single species in two different hyperfine states in a state-dependent optical lattice.
Our new transporter apparatus routinely produces quasi-pure ^{87}Rb Bose-Einstein condensates with up to 10^6 atoms. The movable quadrupole trap coils transport the laser-cooled atoms from the MOT to the science cell, and serve both as part of the MOT and as part of the moving-coil TOP trap (McTOP). Compared to other magnetic trap geometries, the TOP trap allows for good optical access and also is insensitive to the exact positioning of the quadrupole coils.
We avoid the atomic micro-motion intrinsic to TOP traps[3] by transferring a cold thermal cloud from the McTOP trap into a crossed optical dipole trap (XODT) at 1064 nm, where the final evaporation is performed before the optical lattice is adiabatically ramped up. The two linearly polarized XODT beams not only provide external confinement, but they can also be continuously converted into lattice beams by rotating the polarization of the retro-reflected beams relative to the incoming beams via liquid-crystal variable retarders. Together with a third, vertical lattice beam, a three-dimensional simple cubic lattice potential is formed.
We will discuss our recent experimental progress in attaining the superfluid to Mott insulator transition[4], and in creating and characterizing the $N = 1$ Mott insulator state as the starting point for our future studies.

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[4]M. Greiner et al., Nature **415**, 39 (2002)

Observing time reversal in accelerated optical lattices dressed by amplitude modulation

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Cold atoms in accelerated optical lattice potentials usually give rise to localized states, the Wannier-Stark states. Delocalization can be recovered by introducing a resonant coupling among neighboring lattice sites but so far this was demonstrated only applying a modulation to the phase of the lattice potential [1,2]. This results in the coupling at all the orders of the neighboring sites, for instance the first, the second, the third, and so on neighboring sites. On the other hand in many situations it would be preferred a pure nearest neighbor coupling to reproduce the tight binding model.
We show theoretically and experimentally that modulating the amplitude of an accelerated lattice potential at appropriate frequencies allows to implement a pure nearest neighbor coupling among the lattice sites. This gives rise to the coherent delocalization of the trapped atoms and additionally it allows to realize an exact *cosine* energy band. Taking advantage of the specific band dispersion we experimentally demonstrate the time reversal in the expansion of a thermal atomic sample trapped in the optical lattice.
We will also discuss a new measurement of possible deviations from the Newtonian gravity potential at micrometric distances based on cold atoms trapped optical lattices dressed by amplitude modulation.

[1]"Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials" V. V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, Phys. Rev. Lett. 100, 043602 (2008).

[2]"Observation of Photon-Assisted Tunneling in Optical Lattices",C. Sias, H. Lignier, Y. P. Singh, A. Zenesini, D. Ciampini, O. Morsch, and E. Arimondo, Phys. Rev. Lett. 100, 040404 (2008)

Interacting bosons in an optical lattice

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We study a strongly-interacting Bose gas which can be treated by locally paired spin-1/2 fermions [1]. This effective fermion model is analyzed in terms of a mean-field approximation and Gaussian fluctuations. The mean-field solution gives us the phase diagram with the two merging Mott insulators and an intermediate superfluid. The effects of quantum and thermal fluctuations are investigated. Coherent and incoherent branches in the excitation spectrum are found (see Fig. 1). We also consider formation and dissociation of these paired fermionic molecules [2].

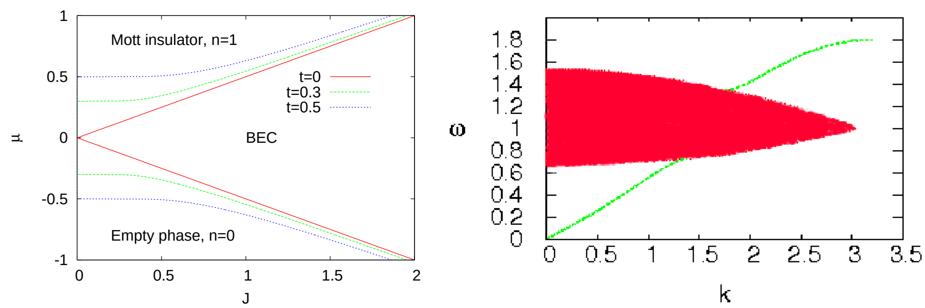

Figure 1: *Phase diagram (left) and excitation spectrum (right).*

[1]O. Fialko, Ch. Moseley and K. Ziegler, "Interacting bosons in an optical lattice: Bose-Einstein condensates and Mott insulator.", Phys. Rev. A 75, 053616 (2007).

[2]K. Ziegler, "Spin-1/2 fermions: crossover from weak to strong attractive interaction.", Laser Physics 15, No. 4, 650-655 (2005).

Staggered-vortex superfluid in an optical lattice

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Solid state systems at low temperatures may possess exotic quantum phases, which involve order parameters with unusual symmetries. One example is the possible $d_{x^2-y^2}$-wave symmetry (staggered flux) in cuprate superconductors[1]. Can optical lattices assist to explore the realms of such quantum phases with manageable experimental complexity? As an example suggesting a positive answer, we discuss how a simple bichromatic light-shift potential can be used to apply angular momentum with alternating signs to the plaquettes of a two-dimensional square optical lattice [2]. We show that in this scenario the dynamics of cold bosonic or fermionic particles is described by a Hubbard model with an additional effective staggered magnetic field. For bosons, besides the uniform superfluid and Mott insulating phases, known from the conventional Bose-Hubbard model, the zero-temperature phase diagram exhibits a novel kind of finite-momentum superfluid phase, characterized by a quantized staggered rotational flux in each plaquette [3]. An extension for fermionic atoms, which leads to an anisotropic Dirac spectrum, may be relevant for the physics of graphene and high-T_c superconductors.

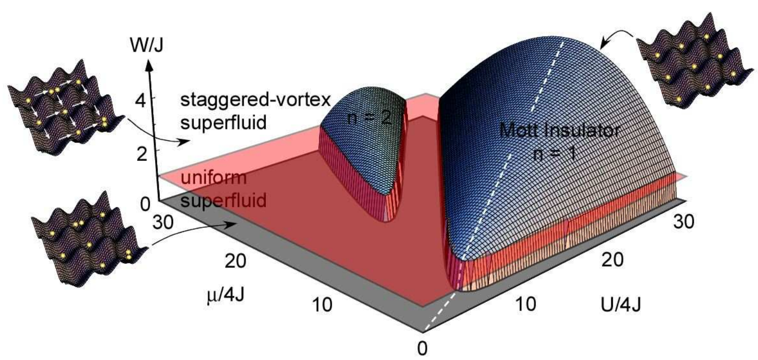

Figure 1: *Phase diagram with respect to the chemical potential μ, the interaction parameter U, the hopping amplitude J, and the scaled magnetic flux W.*

[1] I. Affleck and J. B. Marston, Phys. Rev. B **37**, 3774 (1988).
[2] A. Hemmerich and C. Morais Smith, Phys. Rev. Lett. **99**, 113002 (2007)
[3] L.-K. Lim, C. Morais Smith, and A. Hemmerich, Phys. Rev. Lett. **100**, 130402 (2008)

Mesoscopic Aspects of Strongly Interacting Cold Atoms

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We investigate the heat transport in a heterostructure of trapped bosonic atoms subject to an optical lattice. At finite temperature, the exchange of heat or entropy between different superfluid shells in a wedding cake structure is exponentially suppressed with the size of the Mott layer. However, up to a critical hopping amplitude $t_\star < t_c$, smaller then the critical hopping for the bulk Mott transition, a finite undamped heat current can flow. We discuss the implication of our findings on the temperature aspects in recent experiments.

Quantum dynamics of matter wave emission in optical lattices

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In this work we show that with atoms in an optical lattice it is possible to observe a broad spectrum of different phenomena usually related to light–matter interactions. Here, the role of the matter is played by the absence/presence of one atom in the ground state of the optical potential, whereas the role of light is played by weakly–interacting atoms in a different internal state which are trapped by a different optical potential. The coupling between those two systems is induced by a laser, which simply connects the two internal states of each atom. As we will show, the Hamiltonian that describes this situation is very similar to that describing the interaction between two–level atoms and the electromagnetic field within a photonic crystal.
By changing the laser and optical trapping parameters it is possible to drive the system to different regimes where a rich variety of phenomena can be observed. These include the spontaneous polarization of the system predicted by the mean field theory, collective effects in the emission of atoms from the lattice, and the formation of a bound trapped–untrapped atom state, analogous to the atom–photon bound state that appear when atoms within a photonic crystal (PC) emit photons within the gap region. Moreover, it is possible to reach a regime in which weakly confined atoms drive atom–atom interactions between strongly confined ones, giving rise to effective Coulomb-like interactions between them.

Soliton in a lattice emerging from quantum mechanics

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We study a soliton in an optical lattice containing bosonic atoms quantum mechanically, using both an exact numerical solution and Quantum Monte Carlo (QMC) simulations. The computation of the state is combined with an explicit theory for the measurements of the numbers of the atoms at the lattice sites. In particular, it turns out that importance sampling in the QMC method produces faithful simulations of the outcomes of individual experiments. In a lattice-translation invariant system, under circumstances when classically the ground state is a localized soliton, the quantum ground state is invariant under lattice translations and favors no particular location. Nonetheless, measurements of the positions of the atoms break the translation symmetry, and produce a localized atom distribution. Besides demonstrating our view that measurements are the agent that generates the import of nonlinear phenomena from linear quantum mechanics, this line of thought also opens up new problems. For instance, quantum fluctuations of the atom numbers in a soliton directly contradict the Bogoliubov theory.

Robust quantum phases via three-body recombination

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Cold atoms in optical lattices have the potential to simulate a variety of interesting condensed matter systems. However, prior work has been limited to elastic two-body interactions and higher order, perturbative generation of three- and four-body terms, which are necessary to implement a variety of exotic quantum phases. We consider an inelastic but non-perturbative three-body interaction in optical lattice—three-body recombination—in the context of the lowest band of the Bose-Hubbard model. We find that fast recombination leads to an effective theory in which no more than two atoms are allowed per lattice site, and use this constraint to examine previously inaccessible regions of the phase diagram. We also consider the dynamic generation of novel phases such as a dimer superfluid, described in this work, by adiabatically changing interaction parameters from the well-known Mott insulator phase.

A quantum gas microscope for the simulation of condensed matter systems

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Ultracold atoms in optical lattices provide an exciting new opportunity to study condensed matter physics. These systems are very clean and controllable, and allow for the implementation of idealized theoretical models with high fidelity. Compared to typical real crystals, the lattice spacings of the optical potential are increased by at least three orders of magnitude, bringing optical single site addressability within reach. With such an optical resolution, imaging atoms on single lattice sites allows direct detection of quantum states such as the Mott insulator and antiferromagnetic states or excitations such as spin waves. Additionally it would enable the projection of arbitrary potential landscapes with high spatial frequency as well as efficient spatially resolved manipulation of the atomic ensemble in the trap.

We present our implementation of a quantum gas microscope to experimentally realize high resolution imaging and spatial addressability of a rubidium atom ensemble loaded into an optical lattice. Very good optical access to the atoms combined with solid immersion–like geometry is expected to provide an imaging resolution of about $0.5\,\mu$m. Due to the small depth of field, we realize a two-dimensional quantum gas inside a novel opto-magnetic surface trap using an evanescent wave potential. Despite being only $3\,\mu$m from a glass surface, the condensate exhibits lifetimes of tens of seconds and very low heating rates in this trap.

To create the lattice potential, a projection approach using holographic phase masks is developed. Here, the lattice sites are produced by projecting an intensity pattern through the microscope optics, allowing for high flexibility in the lattice geometries. In analogy to these intensity patterns, phase patterns can also be created. We apply this method to coherently transfer angular momentum to the atom cloud and to produce vortex patterns such as vortex-antivortex pairs or spin textures. Vortex patterns with arbitrary geometry can be created and are detected using a matter-wave interference technique.

Numerical study of Bose-Fermi mixtures in a 3D optical lattice based on the Gutzwiller approximation

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Mixtures of bosonic and fermionic species show the novel quantum effects originated from the interplay between quantum statistics and many-body inter-particle interactions. Quite recently, K. Günter *et al.* studied the quantum phase transition of bosons from a superfluid to a Mott-insulator (MI) using a mixture of bosonic ^{87}Rb and fermionic ^{40}K atomic gases trapped in a three-dimensional optical lattice.[1] Measuring the interference patterns of time-of-flight images, they found that only 10% admixture of fermions diminishes the phase coherence of bosons, which suggests a strong correlation between both species in the mixture.
We have quantitatively analyzed these experimental results [1] on the basis of the three-dimensional Bose-Fermi Hubbard model with harmonic confinement. A highly efficient numerical method based on the Gutzwiller approximation [2] is employed to obtain the many-body ground state of large 3D systems with more than 10^5 lattice sites. Figure 1 shows the results of the average number distribution of atoms in the $y = 0$ plane assuming strongly interacting 1.2×10^5 bosons and 10^4 fermions in the system. In Fig. 1(a), due to the attractive interactions between bosons and fermions, all fermionic atoms localize around the center of lattices and form the band insulator (BI) state (i.e., $n_i = 1$). While in Fig. 1(b), the distribution of bosons is divided into two regions: the high density region around the center ($n_i \approx 5$) where bosons and fermions coexist and the outer MI region ($n_i = 1, 2$). Our calculated results quantitatively demonstrate both distributions of bosons and fermions strongly correlate with each other. We show the systematic analyses of the 3D Bose-Fermi Hubbard model and compare them with the recent experimental results.

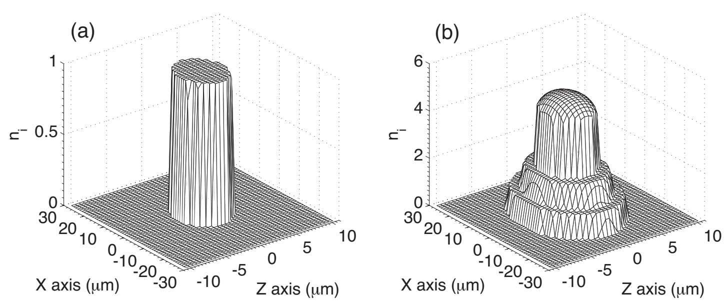

Figure 1: *Average number distribution of Bose-Fermi mixtures in a 3D optical lattice (in the y=0 plane): (a) fermions in the BI phase and (b) bosons in the MI phase.*

[1] K. Günter *et al.*, Phys. Rev. Lett. **96**, 180402 (2006).
[2] M. Yamashita and M. W. Jack, Phys. Rev. A **76** 023606 (2008).

Pump-probe spectroscopy of 1D and 2D optical lattices

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By applying our method of pump-probe diagnostics[1] to the sample of ^{85}Rb atoms in a MOT subject to simultaneously applied optical lattice field, we perform diagnostics of atoms in various confining potentials. With non-resonant pump the diagnostics is nondestructive and can be performed in real-time yielding information on coexistence and competition of non-localized vs. localized atoms and their dynamics in various field configurations. In particular, for atoms in MOT without lattice field the pump-probe spectroscopy yields momentum distribution of atoms (recoil-induced resonances labeled as B in Fig. 1a); with an addition of a second, counter-propagating pump beam the 1D optical lattice is created and we detect additional vibrational structures associated with lattice-localized atoms (resonances V in Fig. 1b). With 2D lattice with stable relative time phases between the lattice beams[2] we see complex spectrum reflecting atomic dynamics in a potential which may have 2D node, or anti-node structure, depending on the polarization of the lattice beams. Fig.1 c depicts spectral structure for 2D lattice with E-vector of all beams in the plane defined by the lattice and probe beams. In this configuration we realize a standard topography of a lattice with potential wells in lattice nodes, but for light polarizations orthogonal to the lattice plane an interesting, anti-node structure is realized[3] which is responsible for very different pump-probe spectra.

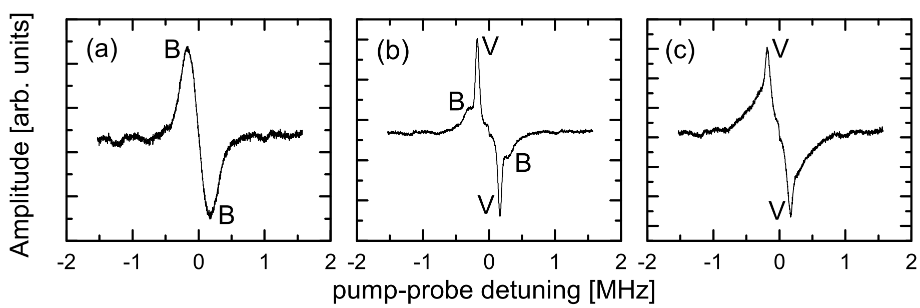

Figure 1: *Pump-probe spectra (a) without lattice field, (b) with 1D lattice, (c) with 2D lattice.*

[1] M. Brzozowska, T.M. Brzozowski, J. Zachorowski, and W. Gawlik, "Bound and free atoms diagnosed by the recoil-induced resonances: 1D optical lattice in a working MOT", Phys. Rev. A **73**, 063414 (2006).

[2] A. Rauschenbeutel, A. Schadwinkel, V. Gomer, and D. Meschede, "Standing light fields for cold atoms with intrinsically stable and variable time phases", Opt. Comm. **148**, 45 (1998).

[3] K.I. Petsas, C. Triché, L. Guidoni, C. Jurczak, J.-Y. Courtois and G. Grynberg, "Pinball atom dynamics in an antidot optical lattice", Europhys. Lett. **46**, 18 (1999).

Resonant Feshbach scattering of fermions in one-dimensional optical lattices

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We consider Feshbach scattering of fermions in an one-dimensional optical lattice [1]. By formulating the scattering theory in the crystal momentum basis, one can exploit the lattice symmetry and factorize the scattering problem in terms of center-of-mass and relative momentum in the reduced Brillouin zone scheme. Within a single band approximation, we can tune the position of a Feshbach resonance with the center-of-mass momentum due to the non-parabolic form of the energy band (see Fig. 1). We present numerical results for resonant scattering in an 1D lattice. In order to understand this results we discuss an analytic model for the coherent tunneling of atoms and dimers in half spaces.

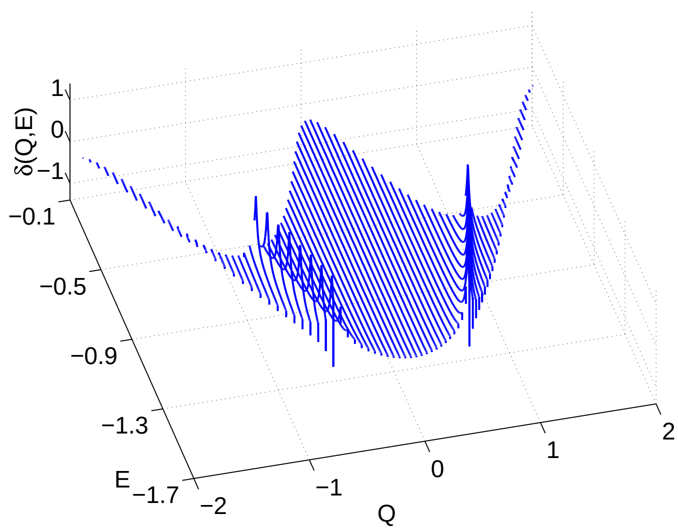

Figure 1: *Even scattering phase-shift $\delta(Q, E)$ of a two-particle Bloch-wave versus energy E and center-of-mass momentum Q. One can see clearly Feshbach resonances symmetrically located around the Q-axis, which disappears when the bound state is outside the band.*

[1] M. Grupp, R. Walser, W. P. Schleich, A. Muramatsu and M. Weitz, J. Phys. B: At. Mol. Opt. Phys. 40 (2007) 2703-2718

Self-trapping of Bose-Einstein condensates in shallow optical lattices

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For the development of possible future microdevices it is important to understand the transport properties of Bose-Einstein condensates (BECs) through guiding structures such as one-dimensional (1D) optical lattices. Such microdevices will be based on internal degrees of freedoms, the basis of spintronics[1], or indeed on the atoms themselves (atomtronics[2]).
We study, both numerically and analytically, the transport of a strongly repulsive BEC through a shallow 1D optical lattice of finite width. This system exhibits a sudden breakdown of the atomic current in the lattice at high interaction strengths. It is investigated how the drop depends on the lattice depth and the interaction strength. We attribute the sudden current drop to the development of a self-trapped state over a few lattice sites. This self-trapped state disappears after a finite time as a result of the finiteness of the lattice. Furthermore, we show that it is possible to prohibit the self-trapping by applying a constant offset potential to the lattice region. The large reduction of the current could potentially be relevant for applications of guided BECs, where the optical lattice acts as a wire between two reservoirs.

[1]S. A. Wolf et al., Science **294**, 1488 (2001)
[2]B. T. Seaman, M. Krämer, D. Z. Anderson, M. J. Holland, Phys. Rev. A **75**, 023615 (2007)

Quantum Phases and Quantum Information of Interacting Atomic Gases in Optical Lattices

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We describe two experiments designed to investigate quantum phases, quantum information and few-body physics using interacting ultracold ^{133}Cs and ^{6}Li atomic gases confined to optical lattice potentials.
The realization of the superfluid to Mott-insulator phase transition with neutral atoms in an optical lattice provides a tantalizing opportunity to test many-body physics with a high degree of accuracy. We report progress on an experimental and quantitative comparison of the superfluid to Mott-insulator quantum phase boundary with results from the Bose-Hubbard model, using Bose-condensed cesium atoms confined to a thin layer of an optical lattice potential. Feshbach resonances with cesium atoms enable us to scan the on-site interaction over a wide range without modifying the tunneling rate and the overall trapping potential; chemical potential can be adjusted by loading a varied mean atomic density into the lattice. We describe the physical apparatus constructed for this investigation, including novel construction designed to achieve precise and agile control of the magnetic field used in tuning interactions, adiabatic loading and manipulation of the lattice potential, and tight two-dimensional confinement applied to negate the effect of gravity without sacrifice in system homogeneity. Further, we describe precise tests of fundamental physics of interacting few-body systems possible in this apparatus.
In addition, we propose a new scheme for quantum information processing utilizing two different atomic species held in two independently controlled optical lattices. One uniformly filled lattice holds fermionic ^{6}Li atoms which act as quantum bits (qubits). A second, less densely populated, lattice holds bosonic ^{133}Cs atoms which mediate entanglement among the qubit atoms. By dynamically translating the second lattice, cesium atoms can be transported to address any lithium atom in the first lattice via contact interactions. In this way, the ^{133}Cs atoms act as quantum messengers among the ^{6}Li atoms. By using these auxiliary messenger atoms, each ^{6}Li qubit can be individually addressed, and any two of the ^{6}Li atoms in the lattice can be entangled through controlled coherent scattering with ^{133}Cs atoms. This system is inherently scalable, as a large number of qubits can be easily addressed, manipulated and transported without qualitative modification to the scheme.

Ground States of Cold Neutral Fermions in 2-Dimensional Optical Lattices: Effects of Strong Correlation in Square and Triangular Lattices

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[2] *CREST (JST), 4–1–8 Honcho, Kawaguchi, Saitama 332–0012, Japan*

The Hubbard model is one of the most fundamental models in the solid state physics. In particular, the single-band Hubbard model with strong repulsive interaction in 2-dimension is a candidate to describe the high-T_c superconductivity whose mechanism has not been understood. Thus, systematic studies are desired to reveal characteristics of this model. We expect that the cold neutral fermionic system gives us a chance to do it because many parameters in this system are highly controllable, e.g., shapes of trap potential, imbalance ratio of spin population, coupling constant.
In this paper, we study ground sates of the single-band Hubbard model with repulsive interaction in various lattice and trap configurations. First, we investigate fermions in the square lattice confined by a box trap[1]. The remarkable issue in this system is a formation of bi-hole pair stripe [2] which has been predicted by Chang and Affleck[3]. To author's knowledge, this is the first confirmation of the prediction. Next, we consider the fermions in the square and triangular optical lattices confined by the harmonic potential. Generally, in this configuration, the Mott core is formed in the center of the trap[4] when the number of particles and the coupling constant are enough large. We study the spin structure of the Mott core with varying the ratio of the spin population. In the triangular trapped system, we find that the Mott core becomes a perfectly polarized core, i.e., the minority is perfectly ejected from the Mott core region, when the imbalance is in a large range. In a middle range, complex spin structures are found in the Mott core, which is not spatially homogeneous. Such a ferromagnetic Mott core and the complex spin structures are never observed in the square lattice case.

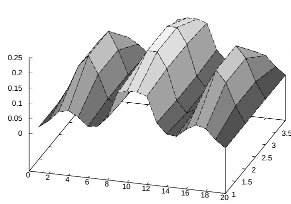

Figure 1: *The result of the hole density profile for $U/t = 5$. The number of doped holes is 8.*

[1] T. P. Meyrath, F. Schreck, J. L. Hanssen, C.-S. Chuu, and M. G. Raizen, Phys. Rev. A **71**, 041604 (2005).
[2] M. Machida, M. Okumura, and S. Yamada, Phys. Rev. A **77**, 033619 (2008).
[3] M.-S. Chang and I. Affleck, Phys. Rev. B **76**, 054521 (2007).
[4] M. Rigol and A. Muramatsu, Phys. Rev. A **69**, 053612 (2004).

Experimental demonstration of single site addressability in a 2D optical lattice with 600 nm period

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Imaging and addressing neutral atoms in the sites of an optical lattice is a prerequisite for various studies on the static and dynamic properties of ultracold quantum gases in periodic potentials. Possible applications range from real space study of tunneling phenomena over quantum simulation to applications in quantum information processing. The small lattice spacing of typically less than 1 μm has so far prevented the direct observation of single sites by optical means.
We have developed a novel microscopy technique that allows for the *in situ* detection of single atoms inside an ultracold quantum gas with a spatial resolution of better than 150 nm. It is based on scanning electron microscopy and employs the electron impact ionization of atoms with subsequent ion detection (see Fig. 1). We present high precision measurements of the density distribution of a trapped quantum gas[1] and show scanning electron microscope images of a condensate loaded in a 1D and 2D optical lattice. The individual lattice sites can be clearly resolved with high contrast and the measured density profile is in good agreement with theoretical calculations. Removing atoms from chosen sites we demonstrate single site addressability in a 2D optical lattice.

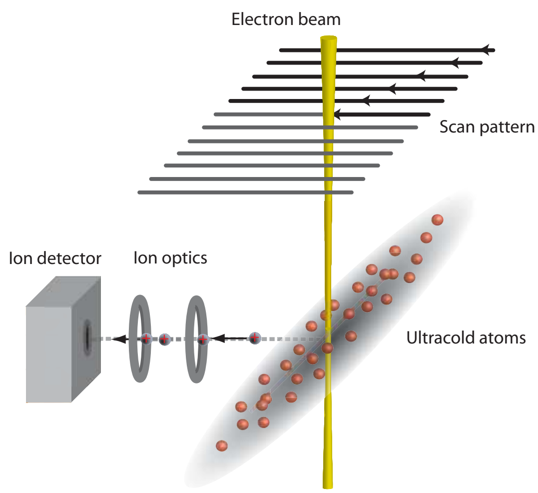

Figure 1: *Working principle of the scanning electron microscope: A focused electron beam is scanned over the cloud and ionizes the atoms which are subsequently detected with an ion detector.*

[1] T. Gericke, P. Würtz, D. Reitz, T. Langen, and H. Ott, *High resolution imaging of single atoms in a quantum gas* arXiv:0804.4788.

Asymmetric Landau-Zener tunnelling and non-exponential decay in a periodic potential

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[3]*CNISM Unitá di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy*
[4]*Cavendish Laboratory, University of Cambridge, Cambridge CB3B 0HE, UK*
[5]*LENS, Via N. Carrara 1, 50019 - Sesto Fiorentino, Italy*
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Landau-Zener tunnelling is a well-known phenomenon in physics and has been studied in a variety of contexts[1]. The Landau-Zener formula presents an analytical solution of the equations of motion for this transition. Here we present experimental and theoretical results on deviations from simple Landau-Zener theory obtained with Bose-Einstein condensates in accelerated optical lattices[2]. We investigated the case of Landau-Zener tunnelling in the presence of nonlinearity which led to an asymmetric tunnelling rate [3](probability of tunnelling from the lower to the upper energy band of the optical lattice is different from the probability for the opposite direction). We also studied the influence of the localisation of the BEC in momentum space on the time dependence of the survival probability in Landau-Zener tunnelling (non-exponential decay as a function of time). In the experiment with the non linear system we observed an asymmetry of Landau-Zener tunnelling. An enhancement of the Landau-Zener tunnelling probability occurs when the atoms tunnel from the lower to the upper energy band while suppression takes place in the opposite direction[4]. This asymmetry is well reproduced by a simple theoretical model taking into account the interaction between the atoms in the BEC. The non-exponential decay experiment investigated the survival probability as a function of time of a BEC initially loaded into the lowest energy band of an optical lattice. We observed deviations from the simple exponential decay curve predicted by the Landau-Zener formula; these deviations are due to the BEC localisation in momentum space. For a BEC whose momentum is well localised inside the Brillouin Zone, step-like discontinuous decay was observed. By inducing a dynamical instability in the BEC we were able to create condensates spread out in the Brillouin zone. When the BEC was no longer contained in a precise region of momentum space (i.e., the occupation area was wider) the visible steps became smoother and less evident. When the BEC filled the entire Brillouin zone, the survival probability as a function of time was again described by a simple exponential curve.

[1]C. Sias, A. Zenesini, H. Ligner, S. Wimberger, D. Ciampini, O. Morsch, E. Arimondo, Physical Letters Review, Vol 98, 120403 (2007)
[2]M. JonaLasino, O. Morsch, M. Cristiani, N. Malossi, J.H. Mller, E. Courtade, M. Andrelini, E. Arimondo, Phys. Let. Rev., Vol 91, 30406 (2003)
[3]B. Wu and Q. Niu, Physics Review A, Vol 61, 023402 (2000), J. Liu et all., ibid. 66, 023404 (2002)
[4]M. Cristiani, O. Morsch, J.H. Mller, D. Ciampini, E. Arimondo, Physical Review A, Vol 65, 063612 (2002)

Flat-top Beams for a Homogeneous Optical Lattice

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Experimental work using quantum gases in optical lattices has been limited by spatial inhomogeneities due to the Gaussian intensity profiles of the lattice laser beams. We have developed a laser beam-shaper that uses a digital micro-mirror device in conjunction with an iterative error diffusion algorithm to generate beams having rms intensity flatness of 0.5% over a significant portion of the beam, as shown in the figure below. Three such systems will be applied to a vacuum system containing a Bose-Einstein condensate in order to generate a homogeneous three-dimensional lattice. The homogeneous lattice will allow us to probe the superfluid-Mott insulator transition with high precision. It will avoid the problems arising from averaging over a wide range of effective chemical potentials that occur when using a lattice with large local fluctuations in depth.
Furthermore, our apparatus will allow us to custom-tailor smoothly varying optical lattice potentials for a wide variety of experimental applications. One such application would be the emerging field of atomtronics[1], in which structures analogous to common electronic devices are created by shaping the potential in which a sample of cold atoms resides.

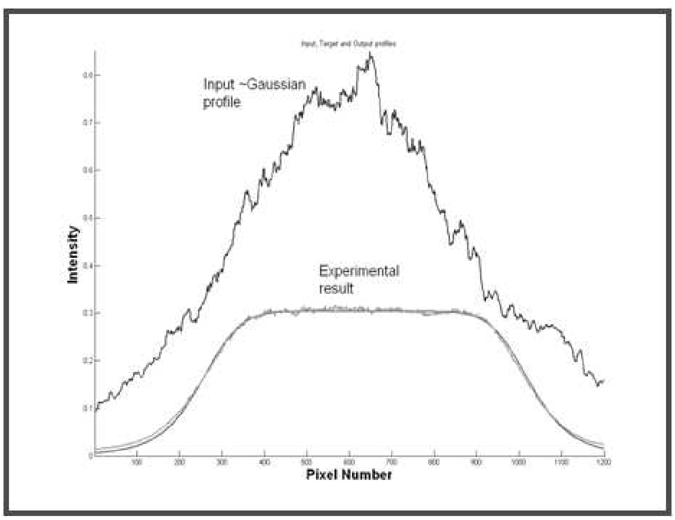

Figure 1: *Noisy Gaussian input beam is converted to output beam with RMS flatness of 0.5% over an area with a diameter of 1700 μm. The target profile, an 8th order super-Lorentzian, is plotted for comparison.*

[1]B. T. Seaman, M. Krämer, D. Z. Anderson, and M. J. Holland, Phys. Rev. A **75**, 023615 (2007)

All-optical 3D atomic loops generated with Bessel light fields

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Circular optical lattices and helical waveguides constitute interesting alternatives for interference experiments with matter waves and quantum transport. They are based on the transfer of orbital angular momentum of light to cold atoms. Recently the use of stationary waves in the angular direction, generated by the superposition of two counter rotating Laguerre Gaussian (LG) beams propagating in the same direction, was proposed as an efficient means of achieving the exchange of angular momentum between light and cold atoms[1]. In this case, the confinement in the radial direction can be achieved optically, but the dynamics along the z axis is completely free. A circular optical potential of this kind would split the wave function of a single localized atom into clockwise and anticlockwise components, which may interfere under certain confinement conditions. On the other hand, a curved helical lattice, which could be generated by the superposition of two identical LG beams propagating in opposite directions, can also be used as an atom guide[2]. Circular and rotating optical lattices have been studied as well, in the context of condensed matter and many particle systems, such as Fermi gases and Bose Einstein condensates [3].

In this work, the propagation invariance of Bessel beams as well as their transversal structure are used to perform a comparative theoretical analysis of their effect on cold atoms for several configurations. We show that, even at temperatures for which the classical description of the atom center of mass motion is valid, the interchange of momenta, energy and orbital angular momenta between light and atoms yields efficient tools for all-optical trapping, transporting and, in general, manipulating the state of motion of cold atoms. For a red detuned far-off-resonance system, the single rotating Bessel beam and the twisted helical lattice are shown to be useful to guide atoms, in the latter case along predetermined separate channels, whereas the 3D stationary circular lattice and the toroidal train lattice can be applied to obtain 3D confinement within a small region of the space. Moreover, in the toroidal train lattice the confinement may be accompanied by a transfer of orbital angular momentum when the detuning is small. Finally, on the basis of our numerical results, we propose an application consisting of the consecutive operation of the different options of light fields in order to create atom circuits or loops in predesigned ways by all-optical means.

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Interacting Mixtures of Bosons and Fermions in an Optical Lattice

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Mixtures of ultracold quantum gases in optical lattices form novel quantum many-body systems, whose properties are governed by the interplay of quantum statistics, inter- and intraspecies interactions, as well as the relative atom numbers of the constituents involved. In our setup, we cool bosonic ^{87}Rb and fermionic ^{40}K to simultaneous quantum degeneracy, giving us access to both Bose-Fermi and Fermi-Fermi mixtures. We study their properties in the combined potential of a blue-detuned three-dimensional optical lattice and a red-detuned crossed dipole trap, allowing for independent control of lattice depth and underlying harmonic confinement.

Bose-Fermi: We have investigated Bose-Fermi mixtures with tunable interspecies interactions in a three-dimensional lattice potential. Distinct ratios of ^{87}Rb to ^{40}K have been prepared at various lattice depths, and interspecies interactions have been tuned over a wide range using a Feshbach resonance. We have identified different regimes of the mixture through the analysis of the ^{87}Rb momentum distribution. Most prominently, we observe a remarkable asymmetry between strongly attractive and repulsive interactions, while for vanishing interactions the fermions become fully transparent for the bosons. On the attractive side, the lattice depth at which the condensate fraction vanishes, shifts towards lower values by up to 10 recoil energies. We attribute this shift to self-trapping of the bosons.

Fermi-Fermi: Spin mixtures of fermionic atoms in a three-dimensional lattice potential can serve as a model system of the Hubbard Hamiltonian. Particularly, the possible realization of a Mott-insulating state makes them highly relevant for solid state physics. We present measurements of both local and global observables on non-interacting and strongly interacting systems. Our results show the existence of conducting and insulating many-body states, and are compared to numerical simulations.

Preparing and Detecting Quantum States with Ultracold Atoms in an Optical Superlattice

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Ultracold atoms in optical lattices have shown to be versatile systems to mimick condensed matter physics. The concept of superlattices for ultracold atoms has recently been realized in experiments and extends the toolbox for the manipulation of the system on the many-body scale. Furthermore, it allows to control effective interactions and dynamics emerging in Hubbard-type models. In our experiments, we combine monochromatic optical lattices on two perpendicular axes with a superlattice on the third axis which is formed by the superposition of two standing light fields with periodicity d and 2d to yield an array of double well potentials. We demonstrate how this bichromatic superlattice can be used to realize effective spin Hamiltonians with controllable spin-spin interactions as well as how to measure the atomnumber distribution within the array by means of interaction blockade. Moreover, we are able to create entangled spin-triplet pairs in the double wells and detect these via the coherent transformation into spin-singlet pairs and back.

Atom Interferometry with an Optical Lattice

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We have developed a new atom interferometer design, in which ^{85}Rb atoms are first cooled in an optical lattice in a MOT. The atoms are released at time $t = 0$, and then subjected at time $t = T$ to an off-resonant standing wave pulse. Around the time $t = (n + 1)T$ for integer $n \geq 1$, we detect the resulting atomic fringe pattern by applying a weak off-resonant optical traveling wave ("readout pulse") and observing the backscattered light from the atomic fringes. Figure 1 shows the resulting signals for $t \approx 2T$ (i.e., for $n = 1$).

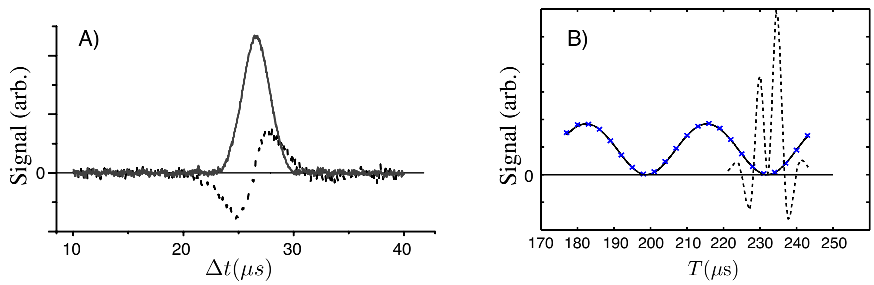

Figure 1: *A) Backscattered signal (solid line) as a function of time Δt from turn-on of readout pulse. Dashed curve shows the signal from previous interferometer configurations.*[1] *B) Peak signal [from A)] as a function of pulse delay T. $\times$'s show data for a short duration pulse ($\tau = 200$ ns), and solid curve is a fit to the data. Dashed curve shows data for a longer ($\tau = 1200$ ns) pulse.*

Theory and expriment tell us that the peak signal as a function of T is periodic in the recoil period $2\pi/\omega_r$, where $\omega_r \equiv 2\hbar k^2/m_{\mathrm{Rb}}$ is the recoil frequency and k is the wave-vector of the light[See Fig. 1B)]. For long pulses, the signal oscillates rapidly as a function of T, in principle allowing a more precise measurement of the recoil frequency. Although the theory only applies to short pulses (satisfying the Raman-Nath condition), we have carried out simulations of our experiment for longer pulses that show good agreement with the data.

We have also measured the maximum signal (as a function of T) for various pulse durations τ. We found that this maximum signal as a function of τ has an oscillatory component with a period of about 6.5 μs. These oscillations were also seen in simulations and the period was found to be close to that of a classical particle oscillating in the approximately harmonic potential near the minima of the potential created by the pulse. Our results may allow us to elucidate the effects of photon scattering on the interferometer visibility.

By collecting data for $n = 1$, 2, and 3, we can deduce the degree of localization of the atoms in the optical lattice just before they are released, and by also measuring the velocity spread, determine whether they are in thermal equilibrium in the lattice.

[1] See, e.g., Cahn *et. al* Phys. Rev. Lett. 79, 784 (1997).

Simulating Relativistic Physics with Ultracold Atoms

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A driving force behind the interest in ultracold atoms is their use as "quantum simulators" of other physical systems, including systems which are experimentally inaccessible in their original manifestations. In this poster, we propose an optical lattice setup under which ultracold atoms would feel effective Diraclike Hamiltonians. Such relativistic Hamiltonians underlie a variety of physical phenomena, ranging from *Zitterbewegung* to spintronics. Creating Diraclike Hamiltonians with cold atoms thus suggests a number of interesting experiments[1], which we outline in this poster.

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Multiplexed quantum repeater

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Quantum communication utilizes quantum entanglement to securely distribute information. The quantum repeater architecture holds promise for long distance quantum communication, however, scalability remains challenging. We have proposed to multiplex memory elements in order to drastically increase entanglement connection rates. We present an experiment demonstrating such multiplexing in cold rubidium.

Single Photon Nonlinearity in Cold Polar Molecular Arrays

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We model single photon nonlinearities in arrays of cold polar molecules via long range dipole-dipole interactions. Decoherences are accounted for by the non-symmetric interaction and symmetric photon-molecule states as well as phonon dispersion. These effects are mitigated in many-body protected manifolds selected with tunable external fields. We discuss the feasibility of this system in optical quantum computation processing as an element of a controlled phase gate.

Progress Towards Spin - Photon Entanglement Using NV Centers in Diamond

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Recent work has demonstrated that individual Nitrogen Vacancy (NV) centers in diamond are promising candidates for quantum register systems. A register, made up of the electronic spin of the NV center and one[1] or few[2] nuclear qubits, may be used to store and manipulate quantum information. The challenge remains to entangle different registers to demonstrate scalability and to carry out more sophisticated functions, e.g. quantum repeaters, and quantum computers. In this work we show progress towards entangling one NV's spin to the photon emitted by the same center as a first step to using photon interference to generate entanglement between different NVs.
Spin-photon entanglement requires good control of the optical transitions of the NV as well as long coherence of the photons in emission. By using resonance fluorescence spectroscopy we identify and study various transitions, to determine their associated selection rules. The properties of these transitions are dependent on the local electric environment and strain, hence differ from NV to NV. Our observations of selection rules for various NVs are in agreement with recent theoretical predictions[3]. We then show that one can resonantly drive controlled optical Rabi nutations by selecting out a particular transition and use this method to obtain information on the coherence of the optical transition. We also show, while exciting an NV off resonantly, one can select out a particular set of transitions in emission and study their optical coherence on an unbalanced interferometer and a cavity.
Finally we propose a method for entanglement generation based on the demonstrated properties of the NV.

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Few-qubit quantum registers encoded in alkaline-earth atoms trapped in an optical lattice

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We propose methods to implement, manipulate, and couple few-qubit quantum registers encoded in alkaline-earth atoms trapped in an optical lattice. The methods rely on long-lived optical qubits and on the possibility of decoupling them from the nuclear spin degree of freedom. Applications in quantum information science and in many-body physics are discussed.

Quantum Repeater based on Atomic Ensembles

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Quantum mechanics provides a mechanism for absolutely secure communication between remote parties. For distances greater than 100 kilometers direct quantum communication via optical fiber is not viable, due to fiber losses, and intermediate storage of the quantum information along the transmission channel is necessary. This lead to the concept of the quantum repeater, proposed in 1998 by Briegel, Duer, Cirac, and Zoller. In 2001, Duan, Lukin, Cirac, and Zoller have proposed to use atomic ensembles as the basic memory elements for the quantum repeater. We will outline our program on the use of atomic ensembles as an interface for quantum information transfer and the prospects for long distance quantum networks.

Optimized planar Penning traps for quantum information processing

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The spins of electrons in an array of planar Penning traps[1] have recently been proposed[2] as qubits for scalable quantum information processing. Such a system, which can be fabricated with existing technology, promises extremely long coherence times since the spin motion is extremely weakly damped ($\gamma_s^{-1} \sim 10^{11}$ s), the electrons are trapped in a cryogenic vacuum environment, and no quantum information is stored in motional degrees of freedom. Via QND coupling to the axial oscillation[3], the spin readout would be performed electronically and with effectively unit fidelity, a technique developed for high-precision measurements of the electron magnetic moment.[4]

Planar Penning traps have only just begun to be studied[5]. Before performing quantum logic operations, it is necessary first to develop for planar traps many of the techniques that have become well-established for cylindrical Penning traps, such as trapping, detecting, and manipulating the spin of a single electron.

As in any Penning trap, it is necessary to minimize the anharmonicity of the axial oscillator[6] so that thermal fluctuations of the axial amplitude do not broaden the axial resonance, which would obscure the signal from a single trapped electron and prevent detection of the small frequency shifts that differentiate its spin states. In a planar trap, anharmonicity compensation is further complicated by the lack of reflection symmetry about the center of the trapping potential.

We seek optimization of planar Penning trap design to establish locally harmonic behavior at a large amplitude, to minimize broadening due to thermal fluctuations of the axial energy, and to minimize sensitivity to the bias voltages applied to compensation electrodes.

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Anyonic interferometry and protected memories in atomic spin lattices

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Systems with topological order can exhibit remarkable phenomena such as quasi-particles with anyonic statistics and might be used for naturally error-free quantum computation. Here we describe how to unambiguously detect and characterize such states in recently proposed spin lattice realizations using ultra-cold atoms or molecules trapped in an optical lattice. We propose an experimentally feasible technique to access non-local degrees of freedom by performing global operations on trapped spins mediated by an optical cavity mode. We show how to reliably read and write topologically protected quantum memory using an atomic or photonic qubit. Furthermore, our technique can be used to probe statistics and dynamics of anyonic excitations.

Mapping photonic entanglement into and out of a quantum memory

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In the field of quantum information science, of significant importance has been the development of scalable quantum networks, composed of quantum nodes for storing and processing information and photonic channels which link the remote nodes for entanglement distribution. Atomic ensembles can play the role of such nodes, where the collective interaction of single excitations and photons provide efficient means for the coherent transfer of quantum states between matter and light[1]. In this contribution, we report two advances toward this goal: entanglement distribution by asynchronous preparation of parallel pairs of atomic ensembles[2], and the reversible mapping of photonic entanglement into and out of atomic memories[3].

By following the seminal proposal by Duan *et al.*[1], two pairs of remote ensembles ($\sim$3 m) at two nodes are each prepared in entangled states, in a heralded and asynchronous fashion by way of conditional control of the quantum memories[2]. After a signal heralding that the two pairs are entangled, the states of the ensembles are coherently converted to propagating fields locally at the two nodes such that they effectively contain two photons, one at each node, whose polarizations are entangled. The entanglement between the two nodes is verified by the measured violation of the CHSH inequality. The effective polarization entangled state is compatible with long-distance quantum communication protocols[1].

Beyond such probabilistic approaches[1], we also demonstrate a protocol where entanglement between two atomic ensembles is created by reversible mapping of an entangled state of light[3]. First, a single photon is split into two modes to generate photonic entanglement. This entangled field state is then coherently mapped to an entangled matter state in two atomic ensembles by way of dynamic Electromagnetically Induced Transparency (EIT)[4]. On demand, the stored entanglement is converted back into entangled photonic modes. The degrees of entanglement for input and output states are explicitly quantified with the transfer efficiency of entanglement approaching 20%. Our approach is inherently deterministic, suffering principally from the finite EIT efficiencies. Moreover, by separating the processes for the generation and storage of entanglement, contamination of atomic entanglement due to multiple excitations can be arbitrarily suppressed with advances in on-demand single photon sources. Our experiment thereby enables an alternative avenue to assist the distribution and storage of entanglement over quantum networks[1].

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Quantum phase gates with polar molecules in an optical lattice

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Polar molecules have attracted significant interest as a viable platform for quantum computing. They combine the advantages of neutral atoms and trapped ions, such as long coherence times, rich level structure, strong optical and microwave transitions, and easy control by DC and AC electrc fields. This combination makes them compatible with various architectures, e.g. optical lattices and solid-state systems. Molecules with large permanent dipole moments can display strong dipole-dipole interactions, allowing for the construction of fast conditional two-qubit gates necessary to realize universal gates.
We analyze a recently proposed physical implementation of a quantum computer based on polar molecules with ”switchable” dipoles , i.e. dipole moments that can be switched ”on” and ”off” (Phys. Rev. A **74**, 050301(R), 2006). ”Switching” is realized by transferring a molecule by e.g. optical excitation between molecular states with significantly different dipole moments. We present a set of general requirements for a molecular system, which would provide an optimal combination of quantum gate times, coherence times, number of operations, high gate accuracy and experimental feasibility. We proceed with an analysis of a two-qubit phase gate realization based on switchable dipole-dipole interactions between polar molecules in an optical lattice architecture. We consider two of the schemes proposed in our previous work, a ”direct” and an ”inverted” scheme. We study the robustness of such a phase gate and analyze the experimental feasibility of the approach, using the CO and LiCs molecules as specific examples. We suggest suitable electronic states and transitions, and investigate requirements for the laser pulses driving them. Finally, we analyse possible sources of decoherence and list practical difficulties of the scheme.

Simultaneous measurements in quantum optics

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Various possibilities for simultaneous measurements of conjugate variables in the optical domain are investigated. Here, for example, the quadratures of the electromagnetic field do not commute and therefore cannot be precisely measured simultaneously. Possible setups, necessary for measuring such non-commuting observables simultaneously by allowing the system to interact with certain classes of ruler systems, are reviewed and discussed. The question arises, which states of the ruler systems are optimal to gain specific information about the investigated system. This leads to generalized versions of the Heisenberg uncertainty relation.

High-Fidelity Readout of Trapped-Ion Qubits

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We present techniques relevant to trapped-ion qubits, and report experimental results utilizing these techniques in $^{40}Ca^+$ and $^{43}Ca^+$. Using a time-resolved photon counting technique we demonstrate single-shot qubit readout with a fidelity sufficient for fault-tolerant quantum computation[1]. For an optical qubit stored in $^{40}Ca^+$ we achieve 99.991(1)% average readout fidelity in 10^6 trials, using time-resolved photon counting. An adaptive measurement technique allows 99.99% fidelity to be reached in 145 μs average detection time. For $^{43}Ca^+$, we propose and implement an optical pumping scheme to transfer a long-lived hyperfine qubit[2] to the optical qubit, capable of a theoretical fidelity of 99.95% in 10 μs. We achieve 99.87(4)% transfer fidelity and 99.77(3)% net readout fidelity.
We will report our progress in performing an entangling gate between a $^{40}Ca^+$ qubit and a $^{43}Ca^+$ qubit held in a single r.f. ion trap.

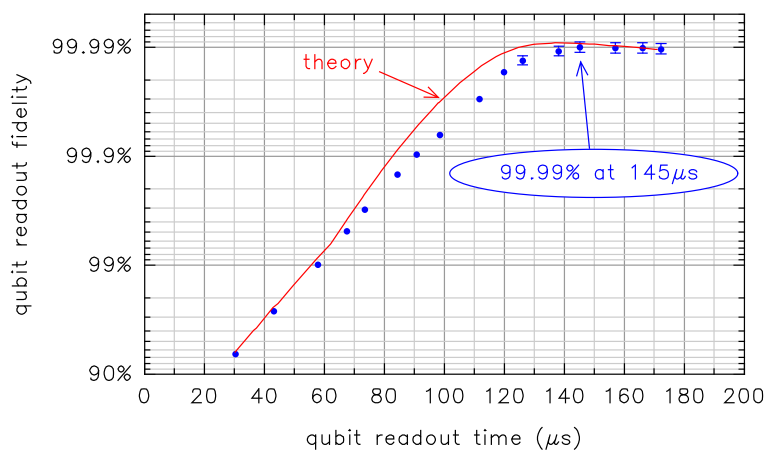

Figure 1: *Average readout fidelity against average readout time for the $^{40}Ca^+$ optical qubit, using adaptive time-resolved photon detection.*

We also generalize the optical Bloch equations so that they can be applied when transitions between pairs of states are driven by lasers with strong sidebands[3]. We show the theory reproduces well the observed response of a cold $^{40}Ca^+$ ion when subject to a single laser frequency driving the $4S_{1/2}$–$4P_{1/2}$ transition and a laser with two strong sidebands driving $3D_{3/2}$– $4P_{1/2}$.

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Two-boson correlations in various quantum traps

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We consider a system of two bosons that is able to model various physical situations by the appropriate choice of both the trapping potential and the interaction between the particles. First, we discuss the contact potential that is usually used to describe inter-particle interactions at ultra-low temperatures. The energy spectra for convex and non-convex confinement potentials are determined and various correlations characteristics are discussed. Entanglement properties are studied particularly carefully. Secondly, we perform an analogous study in the case of Coulomb and other long-range interactions between particles. In all the cases studied, a special attention is paid to the demonstration of the fermionization effects for strongly interacting particles.

Coherent control of electron-nuclear spin qubit registers

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Motivated by recent experiments with single nitrogen-vacancy centers in diamond[123], we consider a few-qubit quantum system composed of a single electron and proximal nuclear spins and we describe a strategy for its efficient control.
Registers comprising a few qubits have gained attention as a possible paradigm for scalable quantum computers. The control of a small number of qubits has been demonstrated in many physical implementations while various proposals for integrating these small units into a larger system have been explored both theoretically [4] and experimentally [5]. These schemes most generally require a *communication* qubit and a few *ancillary* qubits per register, embedded in a hybrid architecture combining optical and solid-state systems. The *communication* qubits couple efficiently to external degrees of freedom (for initialization, measurement and entanglement distribution to other registers), leading to an easy control but at the same time to faster dephasing. The *ancillary* qubits on the other hand are more isolated and they can act as memory or as ancillas in error correction protocols.
Advances in coherent control of single electrons in solid-state systems have permitted to probe their environment[1,2] and to perform entangling operations[3]. The main cause of decoherence is often the nuclear spins [6]. Here we propose not only to reduce the noise by acting on the electronic spin, but also to coherently control part of the environment and use these additional degrees of freedom as qubits. Due to the large hyperfine coupling, the nuclear spins can be addressed individually: The electronic spin thus offers an access to these qubits that are otherwise well isolated and have therefore long coherence times.
The challenges to overcome are to resolve individual energy levels for qubit addressability and control, while at the same time avoiding fast electron dephasing due to the nuclear environment. We describe the system model and present a scheme for achieving these two goals. We analyze feasible performances and practical limitations of this approach in a realistic setting. This hybrid approach combines ideas from quantum optics, mesoscopic physics and NMR to yield a robust, potentially scalable quantum information system.

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Robust Generation of Superposition States

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Ion-trap based quantum information processing is considered to be one of the promising candidates for the large scale quantum computer. Fundamental building blocks, including the qubit initialization, single and two-qubit operation, and state read out have already been demonstrated in the ion-trap system. Much of the recent effort is concentrated in the development of high-fidelity and robust operations.
We report here the experimental results of generation of superposition state in a two level system, $4s\,S_{1/2}$ and $3d\,D_{5/2}$ states, of a single calcium ion. The generation method is based on population transfer via rapid adiabatic passage (RAP), proposed by Vitanov and Shore[1]. The quadrupole transition between the two states is excited with a laser pulse with controlled amplitude shape and linear frequency chirp to steer the initially prepared state to super-position states. The coherence of the generated superposition states is evaluated with Ramsey method. Following the superposition state generation, a π/2-pulse with different phase, ϕ, is introduced to rotate the generated state. Projective measurements of the rotated state showed sinusoidal modulation and fringe visibility of up to 0.93 is obtained. The state generation shows strong robustness with respect to the variation in the Rabi-frequency of the probing laser.
Application of the method in collective addressing of array of ions and in manipulation of "optically-thick" material, including a BEC system, is discussed. The current limitations, including the technical limitations, and state generation speed are also discussed.

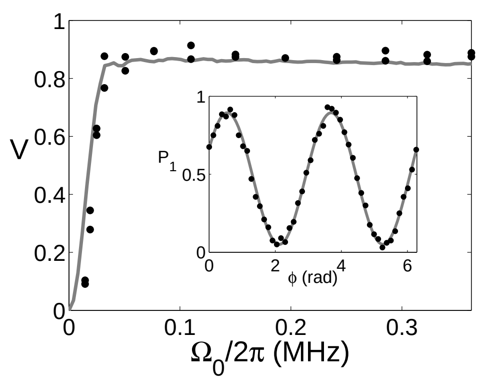

Figure 1: *Coherence measurement of the generated superposition states. Visibility (V) obtained with Ramsey-method for different probe laser Rabi-frequency is shown along with the line showing the simulation result. The inset shows a typical Ramsey fringe observed in the experiment.*

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Studying the Rydberg blockade with individually trapped single atoms in optical tweezers

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In our experiment we want to investigate the Rydberg blockade with two single ^{87}Rb atoms each trapped in an optical tweezer. This effect, recently observed for two single atoms[1], will enable the realization of fast quantum gates[2]. With our experimental apparatus, which allows us to trap single atoms in optical tweezers, to individually manipulate their internal states and to move them around without losing their coherence[3], we have a very versatile tool at hand to explore the blockade mechanism for applications in quantum information processing.

The key element of our setup is a microscope objective with a high numerical aperture. It allows us to focus the dipole trap beam to a waist of less than 1μm, which guarantees the trapping of only one atom per trap[4]. Two separated traps with a variable distance are created by sending two dipole trap beams with an adjustable tilt through the objective. Each trap is separately imaged through the microscope objective onto an avalanche photodiode. When shining in molasses beams, the level of observed fluorescence light tells us about the presence of an atom in each of the traps. Moreover, the tight focusing of the trap beams allows us to individually address the atoms and to drive Raman transitions between the hyperfine levels of the 5S$_{1/2}$ ground state, which form our qubit states.

To investigate the Rydberg blockade regime we study the two-photon resonance for a single atom from the 5S$_{1/2}$ ground level to the 58D$_{3/2}$ Rydberg state. After optically pumping the atom in the F=2, m$_F$=2 state of the 5S$_{1/2}$ ground level, we drive the two photon transition using one π-polarized laser close to the D1-line of Rb (795 nm) which is detuned by 1.2 GHz with respect to the 5P$_{1/2}$, F=2 level and a second σ^+-ploarized laser at a wavelength of 475 nm. A magnetic field of 3.5 G defines the quantization axis. Once in the Rydberg state, the atom is lost from the trap and we observe no fluorescence light when shining in the molasses beams. For two atoms located at a distance of about 3μm we expect a shift of the energy level for the Rydberg-Rydberg system of hundreds of MHz with respect to non interacting Rydberg atoms. The status of the experiment will be reported.

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Controlled Creation of Spatial Superposition States for Single Atoms

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Controlling the quantized centre-of-mass state of a single atom in an array of microscopic potentials has become a focus of experimental and theoretical research in recent years. Optical lattices and microscopic optical or magnetic traps allow one to trap single atoms in individual, well-separated sites between which atoms can coherently move via tunneling. Recently it has been suggested that adiabatic techniques could be used to control tunneling processes with high fidelity analogously to the optical STIRAP [1].
Here, we show how additional degrees of freedom present in an atomic setting can be used to develop new and useful techniques, based on STIRAP, for preparing and processing quantum states. We will show how to create atomic spatial superposition states with a fully controllable phase relation and demonstrate how these technique can be used to construct an atomic interferometer. We will also show how these processes can find applications in quantum computing schemes.

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Entangling single trapped atoms and ions

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When a neutral atom and an ion are brought together, the ion charge induces in the atom an electric dipole moment, which attracts it with an internal-state-independent r^{-4} dependence at large distances. The short-range part of the interaction potential, conversely, presents an intricate dependence on the diatomic molecular state, exhibiting many features known from atomic collision physics, for instance Feshbach resonances[1]. In confined geometries, the bigger interaction strength of the induced-dipole potential, compared to neutral collisions, gives rise to novel phenomena like trap-induced resonances.
An increasing number of experimental groups worldwide are showing interest and/or starting experiments with combined charged-neutral systems in various configurations. This opens up a perspective for manipulating ion-atom systems down to single-particle control.
In this work, we focus on a single trapped ultracold neutral atom and an ion, with the aim of generating and controlling entanglement between them. We analyze the basic interaction mechanisms, solve the eigenvalue problem under variable experimental configurations[2] and discuss how to perform an entangling process exploiting different mechanisms, from phonon exchange between relatively distant traps to trap-induced and Feshbach resonances between quasi-overlapping particles.

[1] Zbigniew Idziaszek, Tommaso Calarco, Paul S. Julienne, and Andrea Simoni, "Quantum theory of ultracold atom-ion collisions".
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Breaking the dipole blockade: Nearly-resonant dipole interactions in few-atom systems

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The dipole blockade, in which Rydberg atom - Rydberg atom interactions inhibit all but a single collective Rydberg excitation, has been proposed as a mechanism to store and manipulate quantum information in mesoscopic ensembles.

In the simplest case of two interacting atoms, the dipole blockade arises from strong dipole coupling to adjacent Rydberg states which, at sufficiently small interatomic separations, shifts the doubly-excited state strongly out of resonance. As a result, when the atoms are excited by a pulsed laser field, they are driven between the two-atom ground state and two-atom singly-excited state with a Rabi frequency that is collectively enhanced by a factor of $\sqrt{2}$.

It would seem reasonable that the presence of further close-by atoms would add to the efficiency of the dipole blockade, allowing only a single Rydberg excitation that is coherently shared among all N atoms, the excitation characterized by a collectively enhanced Rabi frequency of $\sqrt{N}\Omega$. Here we show that this is not necessarily the case $-$ *the presence of a third atom can break the dipole blockade*.

We obtain the molecular states of the three atoms, and identify an *interaction-free, dark state* in which each of the atoms is in a Rydberg state. Using an adiabatic elimination scheme, we derive simple expressions for the three-atom excitation dynamics. We find that the combined interaction of three atoms, each of which pairwise would produce a blockade, breaks the dipole blockade. The dark state plays a critical role in this process.

Several examples will be given that reveal an interesting dependence of the excitation probability on the combined role of atom-field detuning, laser field strength, and dipole-dipole coupling. Moreover, we present numerical simulations that demonstrate the importance of many-atom effects on the excitation dynamics in small ensembles. Our analytical results, together with the many-atom simulations, show that a careful choice of laser parameters must be made in order to optimize the blockade efficiency.

Towards controlled interactions with individual atoms: Detecting nearest neighbors in an optical lattice and controlled atom-field coupling in an optical cavity

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Creating and investigating arbitrary quantum states at will is an intriguing perspective of quantum engineering. This, however, requires ultimate control in preparation, manipulation and detection of quantum systems on a single particle level. Here, we report on recent advances in the detection of individual neutral atoms in adjacent micropotentials of an optical lattice. Further, we present controlled manipulation of single atoms either in spin dependent potentials or by coupling them to a high finesse optical cavity. This opens new routes to tightly control and detect atom-atom interactions in an optical lattice.

In our experiments, we load up to ten laser cooled Cesium atoms from a magneto-optical trap into a 1D optical standing wave. Using fluorescence imaging and real time numerical processing of these images we are able to deduce atomic positions far beyond the standard diffraction limit, even down to nearest-neighbor distances in the optical lattice (~ 435 nm). For manipulation of atoms, we make use of a "magic" lattice wavelength between the D_1 and D_2 lines of Cesium. Together with active polarization control of the laser light forming the optical lattice, this establishes a spin dependent transport[1] for single Cesium atoms which we have performed over up to ten lattice sites.

Finally, in a different approach, we are able to induce a controlled strong interaction between atoms and single photons in a high-finesse optical resonator. This coupling is continuously maintained on a minute time scale and reveals an intriguing intra-cavity dynamics of a single atoms coupled to the cavity field. Moreover, we have established dispersive spin-selective detection of an atom in the cavity. Combining this detection method with our long coupling times paves the way to investigating atom-field coupling in a practically heating free situation at high repetition rates.

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Threshold three photon resonance in Zeeman transitions

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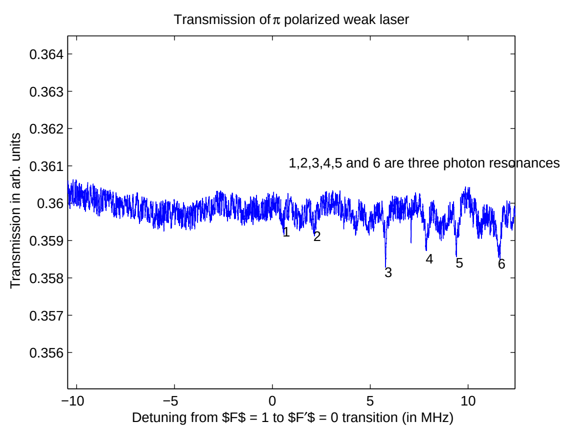
Non-linear light matter interactions in coherent matter shows very different behaviour from such effects in incoherent matter. Coherence between electronic or hyperfine energy levels of gaseous atomic samples can be established through the phenomenon of Electromagnetically Induced Transparency (EIT). In such systems, EIT based Kerr effect, arising from the refractive part of third-order susceptibility in a four-level system, is studied as an absorption in a probe beam modified by signal and coupling beams [1]. We report that such a three photon absorption, shows a sharp threshold around F′ = 0, in Zeeman degenerate transitions of F = 1 and F′ = 0,around the D2 line in ^{87}Rb. The threshold can be attributed to a competition between transparency induced depletion of population in the $m_F = 0$, F = 0 sub-level and off-resonant optical pumping of coherences and population through F' = 1 to this sub-level. The sharpness of this threshold, depends on the nature of coherent state formed. A maximally coherent ground state (a CPT state) creates a sharper threshold. This threshold behaviour may be made use of in making a frequency switch for quantum logic gates.
Three beams L1, L2 and L3, derived from a single laser irradiate a sample of vapour cell Rubidium atoms. L2 and L1 beams show transparency (EIT) of width 1 MHZ at $\delta_{L2} = \delta_{L1}$. Shown in the Figure are absorption features (1-6) seen in L3 beam, of width 200 KHz, at positions of transparency resonances. Scanning the laser frequency using an AOM at any fixed laser position helps in seeing both the EIT and absorption signals. We see in the figure that there is a complete lack of this absorption feature a few MHz red of $F' = 0$,followed by a good contrast absorption at F' = 0 and above. Absorption resonances continue all the way upto $F' = 1$.



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Few-photon photon nonlinear optics with cold atoms inside a hollow core fiber

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Physical processes that can facilitate nonlinear interactions between weak light pulses have been explored for several decades. In addition to fundamental interest, these efforts are stimulated by potential applications ranging from development of few-photon switches and optical transistors to quantum information science. Confining cold atoms and photons to a diameter comparable to optical wavelength inside a hollow core photonic crystal fiber dramatically enhances the probability of interaction between a single photon and a single atom. As a result, an atomic ensemble consisting of a few hundred atoms will create a high optical depth medium that needs only a comparable number of photons to saturate and that can act a mediator for interactions between few-photon pulses. Here, we present an experimental system that uses this novel approach to achieve strong, coherent nonlinear interactions between few-photon pulses and atoms. We study the unique features of this system by demonstrating coherent control techniques such as Electromagnetically Induced Transparency (EIT) and nonlinear all-optical switching with few hundred photons per control/switch pulse.

Entanglement in the adiabatic limit of cavity QED with pairs of atoms

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We analyse the problem of a time dependent 2-atom Tavis-Cummings Hamiltonian in the adiabatic limit. Instead of the usual constant coupling between a single mode cavity and a pair of atoms, we utilise the spatial profile of the interaction by having time dependent coupling functions. In considering the adiabatic limit, we were able to demonstrate the presence of an energy crossing degeneracy which plays a key role in the dynamics[1]. Furthermore, we show that it is possible to achieve conditional entanglement between the cavity and the atoms or generate a maximally entangled state of the two atoms[1,2]. Using the fidelity for particular entangled states, and the concurrence for bipartite and tripartite systems, we derive the properties of entanglement between all three systems. We also study the effect that cavity losses or atomic spontaneous emission have on the system[2].

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Teleportation of resonance fluorescence: bandwidth and squeezing requirements

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The pioneering experimental work of Furusawa et al. on continuous variable quantum teleportation[1] can be looked upon within the framework of the teleportation of quantum fields: there is a continuous beam of light into and out of the teleporter. We take this point of view and ask under what conditions such teleportation may be deemed successful. In this work the scattered field of resonance fluorescence is adopted as the input, since it provides clear signatures (Mollow triplet, photon antibunching), which one can look for in the teleported output. Because the input field is broadband, filtering is essential and we find various constraints on the bandwidths for successful teleportation. The relevant bandwidths involved are those of the input field, correlated EPR fields, Alice's filtering of her photocurrents, and Bob's filtering of the output. We calculate the spectra and intensity correlation functions of the teleported field, and compare them with those of the input field to find the bandwidths and amount of squeezing required for successful teleportation. To calculate the spectra and intensity correlation functions we adopt the method suggested by Ralph[2]. In this method we treat Alice's quadrature measurement signals (photocurrents) formally as operators, which allows us to work with a linear mapping between the input and the output fields . We can then calculate the correlation functions of the output field in terms of those at all inputs (input field and correlated EPR fields). It is worthy of note that this scheme lies in one-to-one correspondence with a treatment of continuous variable teleportation within the framework of stochastic electrodynamics[3]; the former treats all noise processes as quantum operators (both quantized fields and classical currents), while the latter treats them all as classical processes

We first introduce the standard continuous variable teleportation scheme[4], extended to account for the bandwidths and filtering mentioned above. Then we describe the linear mapping between input and output fields and its relationship to stochastic electrodynamics. We derive the spectrum of the output field and show how each bandwidth affects the teleported spectrum. Finally, we derive the teleported intensity correlation function and show the effects of the various bandwidths and degree of squeezing on it. We find very stringent requirements on the relative bandwdiths and the degree squeezing in order to achieve high-fidelity teleportation, particularly of the photon correlations. Optical filtering of the output field by Bob is essential to remove excess noise arising from imperfect matching of Alice's measurement spectrum to the spectrum of squeezing.

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Dicke-Bose-Hubbard model

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We extend the idea of quantum phase transitions of light in atom-photon system with Dicke-Bose-Hubbard model for arbitrary number of two-level atoms. The formulations of eigenenergies, effective Rabi frequencies, and critical chemical potentials for two atoms are derived. With a self-consistent method, we obtain a complete phase diagram for two two-level atoms on resonance, which indicates the transition from Mott insulator to superfluidity and with a mean excitations diagram for confirmation. We illustrate the generality of the method by constructing the dressed-state basis for arbitrary number of two-level atoms. In addition, we show that the Mott insulator lobes in the phase diagrams will smash out with the increase of atom numbers. The results of this work provide a step for studying the effects with combinations of Dicke-like and Hubbard-like models to simulate strongly correlated electron systems using photons.[1]

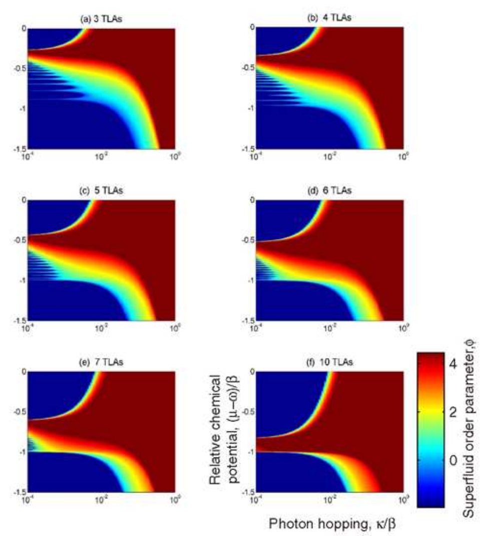

Figure 1: *The phase diagrams for arbitrary number of TLAs, (a)* $N = 3$*, (b)* $N = 4$*, (c)* $N = 5$*, (d)* $N = 6$*, (e)* $N = 7$*, and (f)* $N = 10$*. The notation SF refers to a superfluid phase with strong interaction of photon hopping while MI refers to a Mott insulator phase with equally number of photons in each cavity.*

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Coherent Control of One Atom Strongly Coupled to an Optical Cavity

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Quantum networks based on cavity QED will require robust tools for coherent manipulation of intracavity atoms.[1] In a recent experiment, we demonstrated localization to the ground state of motion for a single cesium atom strongly coupled to the field of a high finesse optical resonator.[2] Our advance was made possible by a Raman scheme tailored to the geometry of the cavity mode. A variation on this scheme provides coherent control over the hyperfine and Zeeman state of the trapped atom. Namely, we use our standing-wave dipole trap as one arm of the Raman pair. We demonstrate how this scheme can be used – in conjunction with efficient hyperfine state detection – to conditionally load one or two atoms into the cavity. We show how incoherent Raman transitions can then be used to prepare the atom(s) in an arbitrary Zeeman state with $\sim 60\%$ efficiency.[3] By driving coherent Raman transitions, we are able to transfer population between the hyperfine ground states of the trapped atom. We are also able to map a superposition of the atom’s Zeeman states onto its hyperfine states, enabling us to retrieve information about the Zeeman coherence. We use Rabi oscillations, spin echo, and Ramsey interferometry to investigate decoherence mechanisms in our experiment. We also discuss the application of our Raman scheme to atom-photon and atom-atom entanglement protocols in cavity QED.

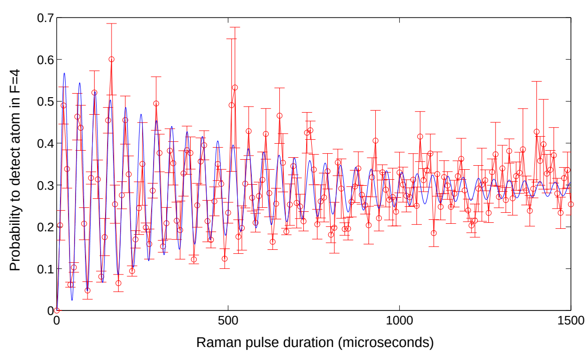

Figure 1: *Rabi oscillation between $|F{=}3,m{=}0\rangle$ and $|4,0\rangle$. For each measurement, atoms are prepared with $\sim$60% efficiency in $|3,0\rangle$, then driven with a raman pulse of varying duration, followed by state detection. A magnetic field along the cavity axis splits the Zeeman levels by $\sim$500kHz. Here the raman pulse is detuned 5kHz to the red of the $|3,0\rangle \leftrightarrow |4,0\rangle$ transition. Decoherence is related to the temperature of the trapped atom.*

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[3] A.D. Boozer, R. Miller, A. Boca, T.E. Northup, and H.J. Kimble, Phys. Rev. A **76**, 063401 (2007).

Generating single-photon nonlinearities and strongly correlated photonic states using nanoscale optical waveguides

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[2] *Niels Bohr Institute, DK-2100 Copenhagen Ø, Denmark*
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A number of methods to guide light that is transversely confined near or below the diffraction limit have been actively explored in recent years. The technologies that have attracted considerable interest include tapered optical fibers, hollow-core photonic crystal fibers, and conducting nanowires that support surface plasmon modes. The tight transverse confinement enables strong interactions between single guided photons and single optical emitters, which can be further manipulated by introducing quantum optical control techniques to these systems. As an example, we show how such techniques can be used to realize strong, controllable interactions between single photons mediated by a single resonant emitter. This nonlinearity can be applied to implement a single-photon transistor, where the presence or absence of a single photon in a "gate" field controls the propagation of a much larger optical "signal" field. Furthermore, we demonstrate that the large optical nonlinearities achievable in these systems can also give rise to strongly correlated states involving many photons. In particular, we describe a method to create a "crystal" of photons beginning from a non-interacting, classical optical pulse. Here, an effective repulsive interaction among the photons causes them to separate and "self-organize" into a crystal. Finally, we investigate the feasibility of creating nanoscale atomic traps using plasmonic systems to form an interface between atomic physics and quantum nano-optics.

Strongly correlated photon transport in nonlinear optical fiber

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We present a theoretical investigation of quantum transport of photons through a one-dimensional waveguide whose propagation is described by the quantum non-linear Schrödinger equation. Such systems are now being implemented using a hollow-core fiber loaded with trapped alkali atoms. The tight transverse confinement of the photonic modes enables a large atom-field coupling strength and correspondingly large atom-mediated optical nonlinearities. These effects are observable at the level of few-photon behavior. In particular, we analyze the quantum correlation functions of a weak classical input field transmitted through a finite system. We observe that the transmitted light exhibits anti-bunching in the presence of *repulsive* interactions between photons, as shown in Fig. 1. This anti-bunching is the consequence of delocalization of photons inside the nonlinear medium and the reflection of bunched components (*i.e.*, two photons) of the input field when the system is tuned to the one-photon transmission resonance. The case of *attractive* nonlinearity shows both bunching and anti-bunching behavior, which arises from competition between the change in mode structure due to nonlinearities and the localization of photons inside the medium. The widely tunable nonlinearity in the system enables one to coherently control statistical properties of photon fields.

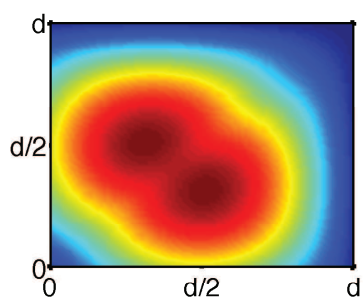

Figure 1: *Due to a positive nonlinearity, photons repel each other. This is manifested in delocalization of the two-photon wave function inside the nonlinear medium.*

Cavity QED with ion Coulomb crystals

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In addition to its fundamental interest for atom-light studies, Cavity Quantum Electrodynamics (CQED) represents an interesting avenue for engineering efficient light-matter quantum interfaces for quantum information processing. Experiments with neutral atoms have been very successful in strongly coupling single atoms to cavities of extremely small mode volume and very high finesse. These experiments are, however, challenged by the difficulty in confining and storing the atoms in the cavity for a long time [1].

Ions, on the other hand, have proved to be an excellent medium for quantum information processing and benefit from very long trapping times, a good localization and are robust against decoherence. Although significant progress has been made within the field and single ions have been coupled to high finesse cavities [2] [3], minimizing the mirror separation, without severely modifying the trapping potential has made it extremely difficult to reach the strong coupling regime with single ions. The small mode volume requirement can be relaxed for ensembles of atoms or ions though, due to the enhancement of the collective coupling strength of the ensemble and clouds of cold ions thus represent an interesting alternative system to a single atom or ion.

When a trapped cloud of ions is cooled below a certain critical temperature, the ions form a spatially ordered state, known as an ion Coulomb crystal. In addition to tight confinement and long storage times, ion Coulomb crystals also have a number of advantages over cold atomic samples. As the ions are confined in a crystal lattice, the decoherence rate due to collisions is very low and their low optical densities (10^8 cm^{-3}) make optical pumping and state preparation unproblematic. Finally, the inherent lattice structure in conjunction with the standing wave field of the optical resonator opens up for new possibilities to engineer the atom-photon interaction.

We will present recent experimental results on CQED with cold ion Coulomb crystals of calcium, obtained by using a novel linear radio frequency trap incorporating a moderately high finesse cavity ($\mathcal{F} \sim 3000$). Even though the 3-mm diameter dielectric cavity mirrors are placed between the trap electrodes and separated by only 12 mm, it is possible to produce *in situ* ion Coulomb crystals containing more than 10^5 calcium ions of various isotopes and with lengths of up to several millimetres along the cavity axis [4]. Single to a few thousands of ions can be stored in the cavity mode volume and efficiently prepared by optical pumping in a given magnetic substate of the metastable $4\mathrm{d}^2\mathrm{D}_{3/2}$ level of $^{40}\mathrm{Ca}^+$. The first results on the crystal-light coupling strength - evaluated by probing the ion-cavity system at the single photon level - as well as the possibilities for CQED experiments offered by this new system, will be discussed.

[1] P.R. Berman (Ed.) Cavity Quantum Electrodynamics, Academic Press inc., London (1994)

[2] M. Keller, B. Lange, K. Hayasaka, W. Lange, H. Walther, Nature **431**, 1075 (2004)

[3] A.B. Mundt, A. Kreuter, C. Russo, C. Becher, D. Leibfried, J. Eschner, F. Schmidt-Kaler, R. Blatt, Appl. Phys. B 76, 117 (2003)

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Novel systems for single-photon generation using quantum memory

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The effective generation of single photons on demand is one of the most important prerequisites for scalable quantum computation and quantum communication using linear optics and measurement-induced nonlinearities. Using atomic memories and the controlled interaction of photons and atoms could allow for the realization of such single-photon sources. One promising approach is based on writing and reading single excitations in atomic ensembles using Raman processes and electromagnetically induced transparency. We report on the development of two novel experimental systems for the realization of such single-photon sources, each combining long coherence times with high efficiencies and purity. The first approach makes use of 1mm-wide paraffin-coated Rubidium cells at room temperature whose volumes are in the order of the interaction region. The second approach makes use of buffer gas cooling to create an appropriate dense medium with excellent coherence properties. Experimental realization and comparison of these two approaches will be presented.

Interference in the light emitted by a single tunneling atom

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We consider the tunneling of a two-level atom in a double well potential while the atom couples to the full continuum of electromagnetic modes in three dimensions (see Fig. 1). The study is within the Lamb-Dicke regime concerning transitions to higher vibrational states, but beyond the Lamb-Dicke regime concerning the tunneling splitting. The tunneling process may decohere, depending on the wavelength corresponding to the internal transition and on the spontaneous emission rate[1]. Interference fringes appear in the emitted light from a tunneling atom, or an atom in a stationary coherent superposition of its center-of-mass motion, if the wavelength is comparable to the well separation and if the external state of the atom is post-selected. If the atom couples to a single electromagnetic field mode of a cavity instead of the full continuum, the coupling between internal and external degrees of freedom of the atom induced by the cavity mode can dramatically change the tunneling behavior[2].

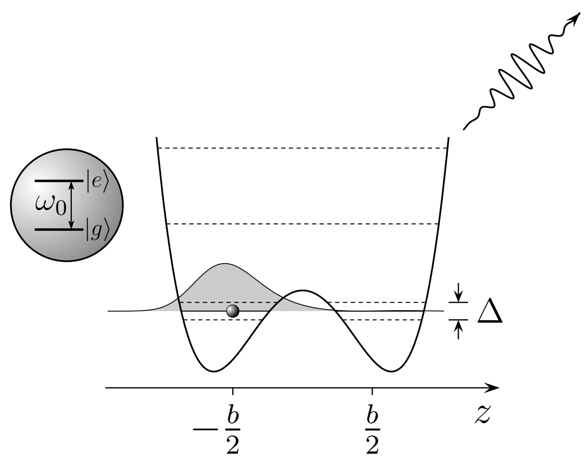

Figure 1: *Emission of a photon by a two-level atom tunneling in a double-well potential.*

[1] D. Braun, J. Martin, Phys. Rev. A **77**, 032102 (2008)
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Fast Excitation of a Coupled Atom-Cavity System

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Single atoms coupled to high finesse optical cavities provide unique systems to study light-matter interactions in the quantum regime. Naturally, these systems are well suited for atom-photon entanglement [1] and distributed quantum networks [2].

Here, we report on the fast excitation of a single atom coupled to an optical cavity using laser pulses that are much shorter than all other coherent and incoherent processes (atom-cavity coupling strength g, atomic polarization decay rate γ, and cavity field decay rate κ). It results in a near-instantaneous promotion of the atom to the excited state. Subsequently, the coupled atom-cavity system displays an oscillatory energy exchange between the atom and the cavity field. Thus, a photon is deposited in the cavity and is finally emitted into a well-defined spatial output mode. The shape of the single photon wavepacket is independent of the excitation pulse and only governed by the dynamics of the coupled atom-cavity system [3].

We show that the cavity frequency can be used as a parameter to control the photon's shape and frequency spectrum. Moreover, the excitation scheme allows us to generate single photons on an atomic cycling transition in a cavity QED environment. It can improve existing atom-photon entanglement experiments[1] by reducing unwanted multiple-photon events and can possibly extend them to multi-photon entanglement protocols. Moreover, a single photon in a superposition of two tunable frequencies as demonstrated here may be useful as a frequency qubit [4].

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Atomic qubit detection in the strong coupling regime

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Microchip based atom traps are a promising approach towards quantum information and communication with neutral atoms. One crucial task for the realization of these protocols is a highly efficient state detection of atomic qubits.

In our experiment we realize the detection of single atoms using a cavity in the strong coupling regime. For this purpose we mount two fiber based cavities onto a micro-fabricated atom chip[1]. We detect single trapped atoms via measuring the transmission of the resonator. Therefore, we load a small ensemble of ^{87}Rb atoms (≈ 10) out of a Bose-Einstein condensate (BEC) into a single antinode of the intra-cavity standing wave dipole trap. The cavity is resonant with the F=2 to F'=3 transition of ^{87}Rb and the atoms are initially in the F=1 ground state. Using weak microwave pulses we transfer single atoms to the F=2 ground state resonant with the cavity. Each time an atom is transferred, we observe a drop in cavity transmission by orders of magnitude which allows to detect the presence of the atom within a few μs with a probability close to unity.

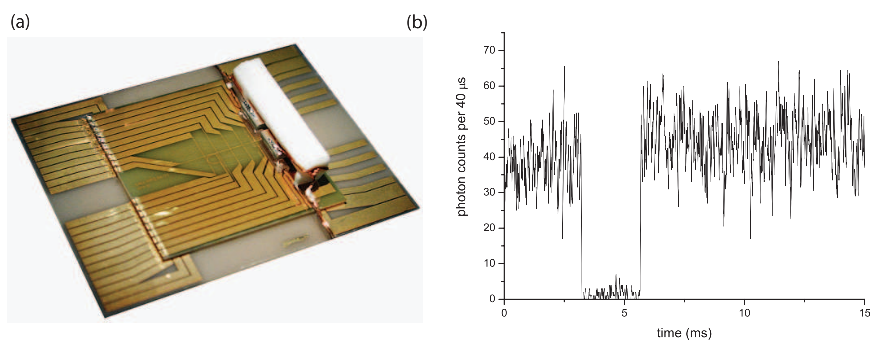

Figure 1: *(a) Setup of the chip and the cavity consisting of two high-reflection coated optical fibers. (b) Cavity transmission measured using an avalanche photo diode. Due to the presence of a resonant atom inside the cavity a large drop in transmission can be observed.*

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Engineering the EIT optical response of a five level atom via two ground state RF transitions

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We consider the linear optical response of a collection of N five level atoms consisting of four different hyperfine ground states and a single optically excited state $|a\rangle$. Following the standard electromagnetically induced transparency (EIT) configuration, one of the ground states, $|c\rangle$, is coupled to the excited state via a strong resonant control beam while the transition between the excited state and a second ground state, $|b\rangle$, is probed by a second, weak laser. Each of these ground states is coupled to an additional ground state via an RF field (see Fig. 1).
As with standard EIT, we find that the strong control beam "dresses" the atom, effectively splitting the absorption profile for the probe beam into two peaks, with a transparency window at the bare transition frequency. However, inside this transparency window two new ultra-narrow absorption resonances arise due to the RF coupling to the additional ground states. The locations and line widths of these new features are fully controlled by the Rabi frequencies of the RF fields and moreover the line widths can be made several orders of magnitude smaller than the natural line width of $|a\rangle$, γ_a. We show how these new resonances and the ultra-narrow line widths can be readily interpreted in terms of the energy eigenstates of the atoms. Near the new features, the dispersion also varies dramatically with the RF field Rabi frequencies. In the case of small RF Rabi frequencies ($\ll \gamma_a$), we predict that in the vicinity of the resulting ultra-narrow features, the probe beam would experience group velocities up to 100 times lower than otherwise possible in an identically configured system without the additional couplings.

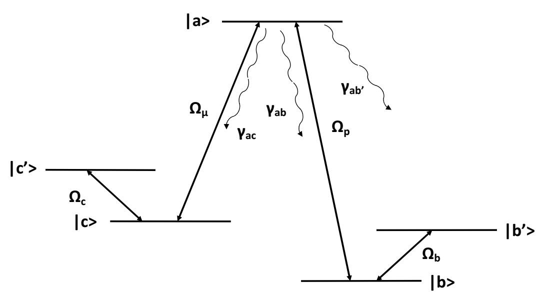

Figure 1: *Our model of a five level atomic system. Here Ω_μ is the strong control beam, and Ω_b and Ω_c are the Rabi frequencies of the new RF fields. The optical response of the system is probed by a laser with Rabi frequency Ω_p, near the $|b\rangle \rightarrow |a\rangle$ resonance.*

Non-Markovian quantum jumps

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Open quantum systems that interact with structured reservoirs exhibit non-Markovian dynamics. We present a quantum jump method for treating the dynamics of such systems[1]. Our approach is a generalization of the standard Monte Carlo wave function (MCWF) method for Markovian dynamics[2]. The MCWF method identifies decay rates with jump probabilities and fails for non-Markovian systems where the time-dependent rates become temporarily negative. Our non-Markovian quantum jump (NMQJ) approach circumvents this problem, provides a simple unravelling of the ensemble dynamics with single histories, and gives interesting insight into the non-Markovian dynamics. To demonstrate our NMQJ method, we study a two-level atom in a photonic band gap material, see Fig. 1.

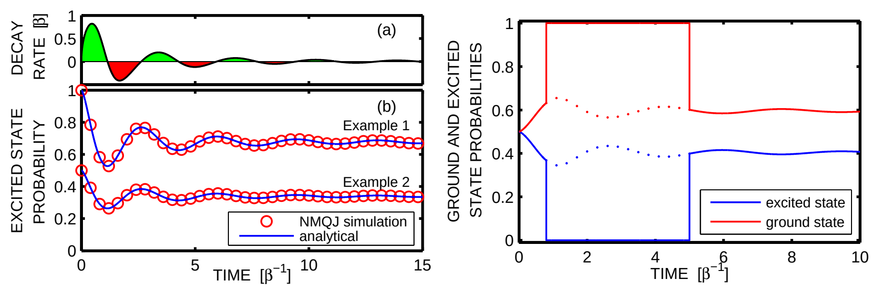

Figure 1: *The demonstration of the non-Markovian quantum jump (NMQJ) method with a two-level atom in a photonic band gap. In the left panel, the upper plot displays the time dependence of the decay rate with temporary negative values, and the lower plot shows the match between the analytical and the simulation results of the excited state dynamics. The right panel shows a single trajectory of the ensemble. Here, the first quantum jump occurs during the positive decay and destroys the superposition state of the two-level atom. The second jump happens when the decay rate has negative value, and this non-Markovian quantum jump restores the superposition which was lost in the earlier quantum jump.*

[1] J. Piilo, S. Maniscalco, K. Härkönen, and K.-A. Suominen, Phys. Rev. Lett. **100**, 180402 (2008).
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Storage and resonance retrieval of optical superposition states in an atomic medium

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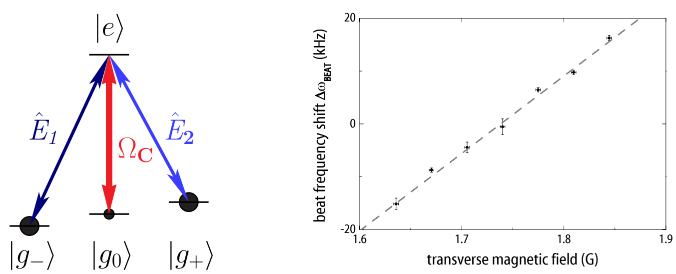
Electromagnetically induced transparency (EIT) is a quantum interference effect that allows for the transmission of light through an otherwise opaque atomic medium[1]. Media exhibiting EIT have remarkable properties, as very low group velocities[2].

We investigate the storage of light in atomic rubidium vapor using a multilevel-tripod scheme as depicted in figure 1(a). As predicted in ref.3, in this system two optical modes propagating with a slow group velocity can exist[3]. In our experiment, which builds upon previous work[4,5], storage of light is performed by dynamically reducing the optical group velocity to zero. After releasing the stored pulse, a beating of the two reaccelerated optical modes is monitored. The observed beating signal oscillates at an atomic transition frequency, opening the way to novel quantum limited measurements of atomic resonance frequencies and quantum switches.



(a) (b)

Figure 1: ***(a)*** *Tripod level scheme. The levels $|g_0\rangle$ and $|e\rangle$ are coupled by one strong control field with the Rabi frequency Ω_C while the two signal fields described by the quantum field operators $\hat{E}_1$ and $\hat{E}_2$ drive the transitions between $|g_-\rangle$ and $|e\rangle$ and $|g_+\rangle$ and $|e\rangle$ respectively. The dots are to indicate the ground state population.* ***(b)*** *Measured beat frequency of the released signal beams, after storage as a function of the applied (transverse) magnetic field. For all shown data points, the atomic sample was irradiated with optical signal fields of constant frequencies for each of the fields during the storage procedure.*

[1] see e.g.: M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Rev. Mod. Phys. **77**, 633 (2005).
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[4] L. Karpa and M. Weitz, Nature Physics **2**, 332 (2006).
[5] L. Karpa and M. Weitz, New J. Phys. **10** (2008).

Coherent magnetic resonance spectroscopy of atomic hydrogen gas

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Spin - polarized atomic hydrogen adsorbed on the surface of superfluid ^{4}He is an ideal realization of a two - dimensional weakly interacting boson gas which is expected to show collective quantum phenomena. Due to the reduced dimensionality, the achievement of high density, necessary condition for the appearance of collective phenomena, seems to be easier than in 3D case.
Recently measurements of the cold collision frequency shift in a doubly spin - polarized hydrogen gas adsorbed on the surface of a ^{4}He film has been realized in Turku [1]. During this experiment electron - nuclear double resonance (ENDOR) spectra were observed. At temperature $T < 80$ mK both absorption and dispersion ENDOR components exhibit an "exotic" behavior. The absorption spectrum has a dispersive line shape, whereas the dispersion spectrum looks like absorption. We explain these observations in terms of coherent interaction of electromagnetic excitation with hyperfine level system of H gas. This is the first demonstration of the electromagnetically induced transparency / absorption in magnetic resonance spectroscopy.
We have elaborated a theoretical model based on the density matrix equations of laser spectroscopy to predict and explain the observed lines. We schematize our atoms as three - level systems in ladder configuration, such that the first and second level are strongly coupled by resonance r.f. field, while the second and the third level are weakly coupled. To the usual linear equation pattern, containing terms describing populations and coherences decay and pumping, we have added some nonlinear terms. The idea of adding nonlinear terms arises from the necessity of considering two processes dramatically affecting the dynamics of the system, which are the three - body recombination, and the presence of the dipolar magnetic field. The latter is proportional to the gas density. The addition of nonlinear terms in the density matrix equations causes a wide spread of profiles in the theoretical ESR susceptibility components and with a proper setting of parameters we obtain theoretical curves matching the experimental ones.

[1]J. Ahokas, J. Järvinen and S. Vasiliev, Phys. Rev. Lett. 98 (2007) 043004

Spectral properties of systems exhibiting intrinsic optical bistability

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Alternative hypothetic mechanisms to give rise to intrinsic optical bistability are studied theoretically as the field-controlled switching between different spectral patterns of the probe beam absorption and fluorescent light. The spectra are calculated both analytically and numerically for the entire hysteresis loop of atomic excitation. The specroscopic analysis is likely to provide graphic distinction between alternative models describing similar hysteresis behaviours. The master equation and equations to find the spectral properties of the non-linear optical response are derived from the Bogolubov-Born-Green-Kirkwood-Yvon hierarchy for reduced single particle density matrices of two-level atoms and quantized field modes and their correlation operators. The hierarchy is treated in the limit of the polarization approximation to make a correct account for radiative relaxation of an atom in the surrounding medium.

Control of the Atom-Cavity Coupling Constant with a Nanopore Lattice in the Cavity-QED Microlaser

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Although a uniform atom-cavity constant is assumed in almost all cavity quantum electrodynamics (QED) theories, atoms in an optical cavity in reality experience position-dependent coupling constants because of the standing-wave structure of the cavity mode. In this work, we have realized precisely controlled atom-cavity coupling constants for cavity QED experiments. We performed this feat by employing an atomic beam aperture[1] in the form of two-dimensional lattice of nanometer holes, i.e., nanopores, with a pitch of 791 nm, the same as the resonance wavelength of atomic barium, in front of the cavity in our cavity-QED microlaser[2]. When the horizontal position of the aperture is adjusted so as to make the vertical columns of nanopores aligned with the antinodes of the cavity, the atoms passing through the holes would experience the maximum coupling. On the contrary, if the columns of nanopores are aligned with the nodes of the cavity, the atom-cavity coupling would vanish. We have demonstrated the microlaser laser operation with adjustable atom-cavity coupling constants in this way. Our technique provides an opportunity to perform various cavity-QED experiments with continuously scannable atom-cavity coupling constants.

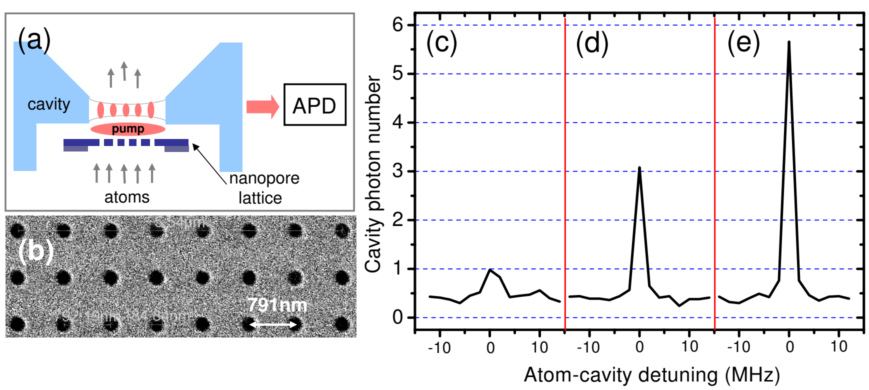

Figure 1: *(a) Experimental setup. (b) Focused ion beam image of the nanopore lattice. The pitch is about 791 nm coinciding with the resonant wavelength of the cavity (or atom), and the diameter is around 200 nm. Observed microlaser signal (mean number of photons in the cavity) when the atoms are localized (c) near the nodes, (d) in-between and (e) near the antinodes.*

[1]O. Carnal et al., Phys. Rev. A **51**, 3079 (1995).
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From a Single-Photon Source to a Single-Ion Laser

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We study a single ^{40}Ca$^+$ ion, confined in a linear Paul trap and coupled to a near-concentric high finesse optical cavity. A drive laser together with the cavity-mode excites an off-resonant Raman transition that connects the $S_{1/2}$ and $D_{3/2}$ levels of the ^{40}Ca$^+$ ion (see Figure). Population gets transferred from $S_{1/2}$ to $D_{3/2}$ while emitting a photon into the cavity. The excitation cycle is closed by a recycling laser that brings the atomic population back to the initial state $S_{1/2}$ after spontaneous emission. Photons leaving the cavity are sent to a Hanbury-Brown&Twiss setup, where mean photon number and second order photon-photon correlations are measured.

In first experiments, we continuously excite the single-ion device and vary the intensities of the drive and recycling lasers. At low external pumping, the system evolves at the boundary of the strong coupling regime where we observe the signature of a quantum laser without threshold. On the other hand, for strong external pumping an intra-cavity photon number exceeding 0.3 is achieved, resulting in a substantial increase in stimulated emission of photons into the cavity. This resembles the mechanism for lasing in conventional lasers. Consequently, we observe threshold behavior of our single-ion device in this regime.

In another experiment, we generate single photons on demand by applying pulsed excitation to the ion. We first generate a photon in the cavity mode by a pulse of the drive laser. The emitted photon subsequently leaves the cavity and the ion is projected onto the $D_{3/2}$ state. A recycling pulse then excites the ion to the $P_{1/2}$ state from which it decays back to the $S_{1/2}$ state. This reinitializes the system and the sequence is repeated. The resulting second order photon-photon correlations reveal the high efficiency of such a single-photon source and agrees with theoretical simulations of the process.

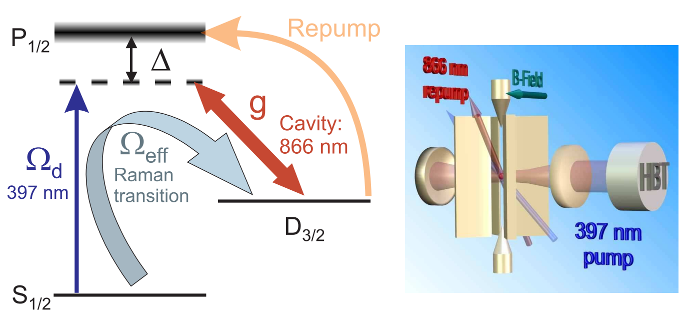

Figure 1: *A single ^{40}Ca$^+$ ion coupled to a high-finesse cavity.* ***Left:*** *Level and excitation scheme.* ***Right:*** *Schematic experimental setup.*

Strong magnetic coupling between an electronic spin qubit and a mechanical resonator

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Techniques for cooling and manipulating motional states of a nano-mechanical resonator are nowadays actively explored, motivated by ideas from quantum information science, testing quantum mechanics for macroscopic objects and potential applications in nano-scale sensing. Here we describe a technique that enables a coherent coupling between a single electronic spin qubit associated with a nitrogen-vacancy impurity in diamond and the quantized motion of a nano-mechanical resonator. The basic idea can be understood from the prototype system shown in Fig. (1). Here a single spin is used to sense the motion of the magnetized, vibrating tip, that is separated from the spin by an average distance $h \approx 25 - 50$ nm. Oscillations of the tip produce a time-varying magnetic field that causes Zeeman shifts of the spin qubit. Under realistic conditions the shift corresponding to a single quantum of motion can approach 100 kHz and exceed both the electronic spin coherence time ($T_2 \sim 1$ ms) and the intrinsic damping rate, $\kappa = \omega_r/Q$, of high-Q mechanical resonators. In this regime, the spin becomes strongly coupled to mechanical motion in direct analogy to strong coupling of cavity QED.

We describe how this regime can be achieved in a practical setting specifically addressing the issues of fast dephasing ($T_2^* \sim 1\,\mu$s) of the electronic spin due to interactions with the nuclear spin bath. Under such conditions strong coupling can be achieved by a careful preparation of dressed spin states which are highly sensitive to the motion of a magnetic resonator but insensitive to perturbations from the nuclear spin bath. In combination with optical pumping techniques, the coherent exchange between spin and motional excitations enables ground state cooling and the controlled generation of arbitrary quantum superpositions of resonator states. In addition, optical spin readout techniques provide a general measurement toolbox for the resonator mode with quantum limited precision.

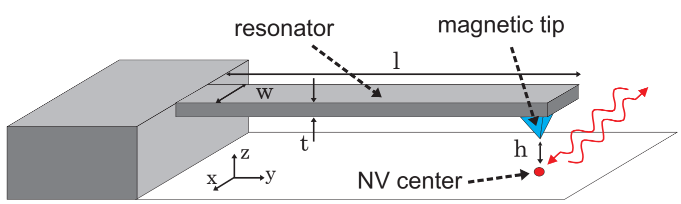

Figure 1: *A magnetic tip attached to the end of a nano-mechanical resonator of dimensions* (l, w, t) *is positioned at a distance* $h \sim 25$ *nm above a single NV center, thereby creating a strong coupling between the electronic spin of the defect center and the motion of the resonator. Microwave and laser fields are used to manipulate and measure the spin states.*

Interaction between neutral atoms and superconducting surfaces

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An atom close to a dielectric or metallic surface experiences magnetic field fluctuations arising from thermally-induced noise currents. The origin of those noise currents is connected with the finite resistivity and the skin depth of the substrate.

The use of superconducting films has been proposed as a way to reduce thermally-induced noise[1]. As the resistance of a superconductor is ideally zero, there should be no thermally-induced noise and the cryogenic temperature would help to reduce heating and background collisions. However, most practical applications of superconductivity demonstrate that dissipation phenomena can take place in superconductors. In particular, thin superconducting films can be regarded as two-dimensional (2D) systems where fluctuations resulting from bulk losses seem to be negligible and the dominant noise source is given by vortex motion.

Neutral atoms are shown to be ideal candidates to probe the magnetic field due to vortices in thin superconducting films close to the Kosterlitz-Thouless-Berezinskii transition temperature. The relaxation time T_1 of the Zeeman sublevel populations, (due to thermally induced spin-flip transitions), and the transverse relaxation time T_2 for Zeeman coherences are shown to be very useful in the study of the vortex dynamics[2].

Moreover, the relaxation time T_1 depends on physical parameters such as the penetration depth, the thickness of the superconducting layer and the atom-surface distance. The lifetime T_1 has been calculated for a d-wave superconductor which has an anisotropic penetration depth. The analysis of such lifetime allows to define a screening factor as a function of the layer thickness which can be compared with the case of a half planar metal.

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Strong coupling of single optical emitters to nano-scale surface plasmons

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[2]*P. N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, 119991, Russia*
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[4]*Electrical Engineering Department, Texas A&M University, College Station, TX 77843, USA*

We present an experimental observation of strong optical coupling between individual, nanocrystal CdSe/ZnS quantum dots, as well as Nitrogen-Vacancy color centers in diamond nanocrystals, and the guided surface plasmon modes of a proximal silver nanowire. The strong coupling between emitter and field is enabled by the unique properties of the plasmon modes on these nanowires. In particular, due to the small size of the nanowires ($\sim$100 nm in diameter), the surface plasmons are localized transversely to dimensions well below the diffraction limit. An enhancement of the Purcell factor of the system and photon correlations consisten with a single-photon source are observed, and a realistic theoretical model for these processes is presented.

Single-Photon Bus between Spin-Wave Quantum Memories

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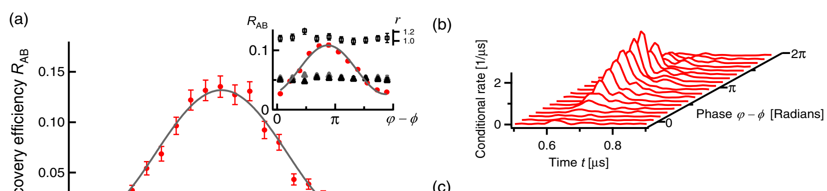
Generation of non-classical correlations (entanglement) between atoms [1] photons [2], or combinations thereof[3], is at the heart of quantum information science. Of particular interest are material systems serving as quantum memories that can be interconnected optically[4] An ensemble of atoms can store a quantum state in the form of a quantized collective spin excitation (magnon), that can be mapped onto a photon[5] with high efficiency [6]. Here we report the phase-coherent transfer of a single magnon from one atomic ensemble to another via an optical resonator serving as a quantum bus that in the ideal case is only virtually populated. Partial transfer deterministically creates an entangled state with one excitation jointly stored in the two ensembles. The entanglement is verified by mapping the magnons onto photons, whose correlations can be directly measured. These results will enable deterministic multipartite entanglement between atomic ensembles.



(c)

p_{00}	p_{10}	p_{01}	p_{11}
0.88(1)	0.08(1)	0.030(4)	0.0005(2)

Figure 1: *(a) Recovery efficiency of joint readout of two ensembles, versus readout phase difference. High contrast sinusoidal variation indicates large degree of coherence between the two samples. Inset: Recovery efficiencies of samples read out individually. (b) Time dependence of readout, versus readout phase. (c) Table of all non-negligible diagonal elements of system density matrix, indicating supression by a factor of 4 of two-magnon events.*

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[1]Matsukevich *et. al.*, Phys. Rev. Lett. **96** 030405 (2006); Chou *et. al.*, Nature **438**, 837 (2005).
[2]Marcikic *et. al.*, Phys. Rev. Lett. **93** 180502 (2004)
[3]Blinov *et. al.*, Nature **428** 153 (2004); Matsukevich *et. al.*, Phys. Rev. Lett. **95** 040405 (2005).
[4]Julsgaard *et. al.*, Nature **413** 400 (2001).
[5]Duan *et. al.*, Nature **414** 413 (2001); Black *et. al.*, Phys. Rev. Lett. **95**, 133601 (2005); Thompson *et. al.*, Science **313**, 74 (2006); Chaneliere *et. al.*, Nature **438** 833 (2005)
[6]Simon *et. al.*, Phys. Rev. Lett. **98** 183601 (2007)

Single Atom and Photon Interactions Using a Toroidal Microresonator: A Photon Turnstile

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Significant advances in quantum information science have been achieved through matter systems that mediate single photon interactions.[1] In this contribution we demonstrate the use of a microtoroidal optical resonator to achieve a robust, efficient mechanism for regulating the transport of photons one by one. We also use computer simulations to examine the effect of surface-induced van der Waals forces on our atom-cavity system.

In our experiments we monitor the effect of single CS atoms transiting close to a microtoroid critically coupled to a tapered fiber. As opposed to the strong coupling regime where the atom-cavity coupling rate, $\underline{g}$, dominates all other dissipation rates, we operate in the so called 'bad-cavity' limit where the coupling of the cavity to the input-output modes dominates ($\kappa \gg \underline{g}$). The atoms interact with the fields of the resonator and regulate photon statistics by means of an interference effect involving the directly transmitted optical field, the intracavity field in the absence of the atom, and the polarization field radiated by the atom.[2] Photon counting measurements verify the transformation from a Poissonian to a sub-Poissonian photon stream. This dynamical mechanism to create the photon turnstile requires only that the intracavity atomic absorption be large and is thus robust against experimental variations in the atom-cavity coupling.

Additionally, numerical simulations modeling surface-induced van der Waals interactions between the toroids and Cs atoms indicate that these forces reduce the effective atom coupling, $\underline{g}_{eff}$, by $\sim$2x. These results serve as a guide for future experiments that could directly probe surface interactions or investigate the possibility of atom trapping near the toroid surface.

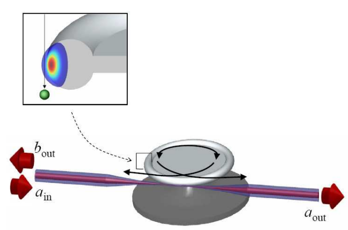

Figure 1: *A schematic of the experimental setup showing the microtoroid coupled to the tapered fiber and the associated input and output modes. Falling Cs atoms passing close enough to the toroid interact with the evanescent field (inset).*

[1] H.J. Kimble,"The Quantum Internet.", Nature Insight Review (2008).
[2] Dayan et. al., Science **319**, 1062 (2008).

Protecting entanglement via the quantum Zeno effect

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Entanglement is a quantum correlation between two or more parts of a composite quantum system. Erwin Schrdinger described it as "the characteristic trait of quantum mechanics, the one that entails its entire departure from classical lines of thought". During the last few decades the potential of entanglement for new quantum technologies has been explored, paving the way to new areas of physics combining information theory and communication technology with quantum mechanics.
Entanglement is, however, a very delicate property. Any interaction of quantum systems with their environment inevitably destroys it. Since no quantum system is completely isolated from the external environment, the preservation of entanglement may seem an insurmountable problem.
We have demonstrate that entanglement can be effectively protected from the harming effects of the environment by using a purely quantum phenomenon, known as the quantum Zeno effect. The quantum Zeno effect states that repeated and frequent measurements of the state of a quantum system, aimed at checking whether the system is still in its initial state or not, may freeze its dynamics [1]. As the saying goes "A watched pot never boils".
Interestingly enough a similar conclusion holds if appropriate measurements are performed on the environment rather than on the system itself. Our results demonstrate that the entanglement of two quantum bits (qubits) can be protected from entanglement deterioration simply by monitoring the environment. Instead of watching the pot we watch the stove flame. Specifically we consider two entangled atoms in a lossy cavity and we prove that monitoring the cavity field leads to entanglement protection [2].

[1]B. Misra and E.C.G. Sudarshan, J. Math. Phys. **18**, 756 (1977)
[2]S. Maniscalco, F. Francica, R. L. Zaffino, N. Lo Gullo, and F. Plastina, Phys. Rev. Lett. **100**, 090503 (2008)

Polarity manipulation of Atom-Cavity Coupling Constant in the Cavity-QED Microlaser

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In the study of cavity quantum electrodynamics (QED) only the absolute value of atom-cavity coupling constant has been considered since in all of the experiments so far such as cold single atoms in a cavity[1] the coupling constant is treated as unipolar. In the present study, we ask what happens if the coupling constant is bipolar in the cavity-QED microlaser.[2] Obviously, if the coupling constant changes its sign once in an anti-symmetric way during the atom-cavity interaction time τ, the pulse area of the cavity field seen by the atom would be zero, and thus a lasing would not occur. We show, however, that a maximum gain can be achieved with a proper atom-cavity detuning in this case. In our experiment performed with a TEM_{10} cavity mode interacting with the $^1\mathrm{S}_0$-$^3\mathrm{P}_1$ transition (791 nm) of atomic barium, we observed a minimum lasing on resonance whereas a maximum lasing occurs when the detuning is equal to $1/(\sqrt{2}\tau)$. Our results can be well explained in terms of semiclassical Bloch vector picture.

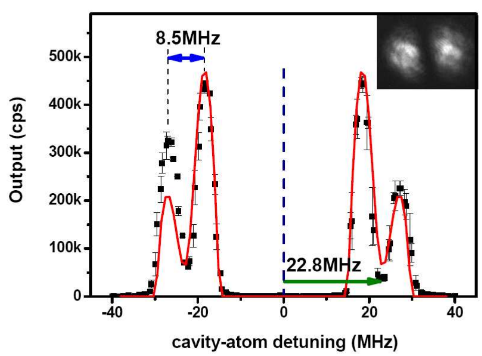

Figure 1: *Cavity-QED microlaser output versus atom-cavity detuning for a TEM_{10} mode. Solid line is a fit curve based on a semiclassical microlaser theory. The signal at detuning of $\pm$22.8 MHz corresponds to on-resonance condition, exhibiting a minimum lasing signal. The separation between two peaks around the minimum point is 8.5 MHz, consistent with theoretical prediction. The inset is the far-field image of the output signal.*

[1]G. R. Guthöhrlein et al., Nature **414**, 49 (2001);P. Maunz et al., Opt. Lett. **28**, 46 (2003);T. Puppe et al., Phys. Scr. **T112**, 7 (2004);S. Nußmann et al., Phys. Rev. Lett. **95**, 173602 (2005);T. Puppe et al., Phys. Rev. Lett. **99**, 013002 (2007).

[2]K. An, J. J. Childs, R. R. Dasari, and M. S. Feld, Phys. Rev. Lett. **73**, 3375 (1994); W. Choi et al., Phys. Rev. Lett. **96**, 093603 (2006).

Coherent Manipulation of Single Atoms in Cavity QED

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Cavity QED systems consisting of neutral atoms coupled to high finesse optical microcavities have important applications to quantum information processing and communication. We have developed an experimental apparatus with trapped atoms in a high finesse cavity in the strong coupling regime. We have demonstrated deterministic loading and storage of individual atoms delivered from a magneto-optic trap to the resonator using an atom conveyor [1].

In this poster, we present our progress towards realizing a two atom quantum gate utilizing dual neutral atom registers in a high finesse optical cavity. The framework for achieving this goal is to have the ability to couple two atoms to the same cavity mode via individual conveyors with independent control which can be seen in Fig. 1.

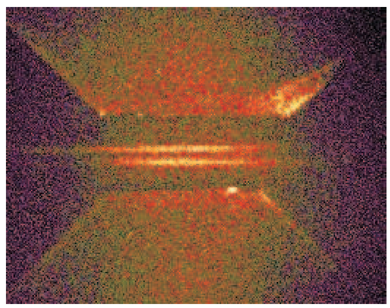

Figure 1: *Florescence image of two lattices between two cavity mirrors.*

Our endeavors have branched out to indepth studies of the optical lattice. Noise measurements have shown that lifetimes are limited by instabilities in the axial direction of the trapping potential. With continuous cooling, lifetimes are extended from 60 s to 300 s, limited only by background collisions.

[1] K. Fortier, S. Kim, M. Gibbons, P. Ahmadi, M. Chapman, Phys. Rev. Lett. **98**, 233601 (2007).

Restoring the wave function with Cavity QED of single Yb atoms

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Quantum measurement, i.e., non-unitary process, has been believed to be irreversible. However, Royer found a method of restoring the wave function even after the measurement process[1,2]. Such a measurement can be implemented for single 1/2 spins by using Faraday rotation[3]. Since the information on the spin direction can be extracted through the Faraday rotation of optical probe pulses, the spin state changes in a non-unitary manner. However, if the rotation angle is small (measurement is weak), successive measurements probabilistically cancel the measurement effect and the premeasurement state is restored completely.
To implement such a reversible measurement, the detection of Faraday rotation due to a single 1/2 spin is inevitable, that is, a cavity QED system is required. Here we report on real-time detection of single Yb atoms with a cavity QED system, which is the first step to realize the reversible measurement. The Yb atoms have several merits for the spin manipulation, one of which is a longer coherence time compared with alkali-atoms. This is because the ground state of Yb atoms is diamagnetic, and the magnetic moment has its origin only in nuclear spin. We select the ^{171}Yb isotope, which posseses 1/2 nuclear spin.
The outline of our experiment is as follows: we first trap Yb atoms in a magneto-optical trap (Upper MOT) with $^1S_0$-$^3P_1$ intercombination transition (556nm). Atoms released from the upper MOT are recaptured with the lower MOT which is located just above a high-finesse Fabry-Perot cavity. Ultraslow atoms are dropped into the cavity and their transits are detected. Our cavity shows the finesse of about 1×10^5 at 556nm, and the cavity length is stabilized at 150 μm. The resulting atom-cavity coupling g, the cavity-field decay rate κ, and the dipole decay rate γ are $(g, \kappa, \gamma)/2\pi$=(2.8, 4.8, 0.09) MHz, respectively. In the presentation we will also report the observation of Faraday rotation with single Yb atoms.

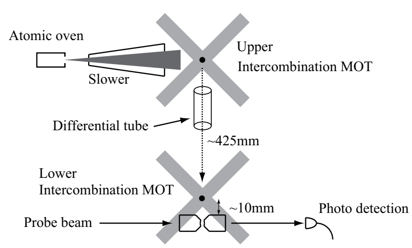

Figure 1: *Schematic diagram of the experiment.*

[1]M. Ueda and M. Kitagawa, Phys. Rev. Lett. **68**, 3424 (1992).
[2]A. Royer, Phys. Rev. A **73**, 913 (1994).
[3]H. Terashima and M. Ueda, Phys. Rev. A **74**, 012102 (2006).

Precessing magnon as a heralded quantum memory for photon polarization states

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A collective excitation of an atomic ensemble (a magnon) may be strongly coupled to a single mode of the electromagnetic field. This makes a magnon an ideal format with which to store a photonic quantum state; the conversion to and from a photon is facilitated by the collective strong coupling. Single excitations have routinely been stored as magnons and retrieved as single photons after a programmable delay[1]. Transfer of a magnon from one atomic ensemble to another via an optical resonator has also been demonstrated[2]. The versatility of the system, however, is limited by restrictions on accessible photon polarization states due to the phase matching requirement necessary for strong coupling. Here we demonstrate the precession of a magnon state which removes such restrictions and, using this technique, realize a heralded quantum memory for arbitrary (unknown) polarization states. We optically pump an ensemble in a rotating frame and generate a precessing magnon that corresponds to the input polarization state. The stored state is later recovered in the form of a single photon with a state-independent polarization fidelity of $90(2)\%$. The single photon nature of the recovered photons is confirmed by a conditional autocorrelation measurement yielding $g_2 = 0.24(5)$, a four-fold suppression of two-photon events compared to a Poisson distribution. The quantum memory demonstrated here may serve as one of the key building blocks for distributed quantum networks and quantum computers.

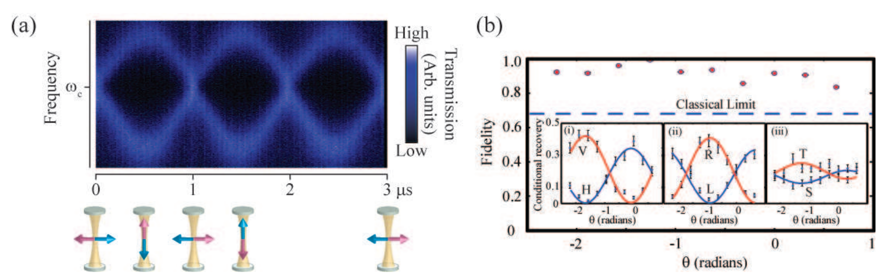

Figure 1: *(a) The precession of the ensemble is observed as a variation of the vacuum Rabi splitting in the transmission spectrum of a weak probe beam through the optical resonator. (b) The polarization fidelities for different input states* $|\psi\rangle = \cos(\theta + \frac{\pi}{4})\,|R\rangle + e^{i\phi}\sin(\theta + \frac{\pi}{4})\,|L\rangle$ *for a fixed* ϕ, *calculated from the projection of output states in three orthogonal bases, H-V, L-R, and S-T (insets i, ii, and iii, respectively).*

[1] A. Kuzmich *et. al.*, Nature **423**, 731 (2003); M. D. Eisaman *et. al.*, Nature **438**, 837 (2005); J. Simon *et. al.*, Phys. Rev. Lett. **98**, 183601 (2007).

[2] J. Simon *et. al.*, Nature Physics **3**, 765 (2007).

Observation of atom-cavity interaction with cold single atoms with various coupling constants

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Exceptional point(EP) where the energy-level crossing and avoided crossing coalesce has drawn much interest in the study of quantum systems described by non-Hermitian Hamiltonian.[1] Atom-cavity system with non-negligible damping is also described by non-Hermitian Hamiltonian, and thus it is of considerable interest to observe an EP and to explore possible non-singular atom-cavity interaction around the EP. Toward this end, we have devised ways to vary the coupling constant g between the atom and the cavity in order to achieve EP condition $g = |\gamma_c - \gamma_p|/2$, where $2\gamma_c$ is the cavity decay rate and γ_p is the half width of the atomic transition. For the maximum coupling constant g_0 achieved in our experiment with atomic rubidium, relevant parameters were $(g_0/2\pi, \gamma_c/2\pi, \gamma_p/2\pi)$=(16, 19, 3) MHz for a cavity with a finesse of 25000 and a length of 155 μm, and thus the strong coupling condition, $g > |\gamma_c - \gamma_p|/2$, was satisfied. We could change the coupling constant by selecting either σ or π atomic transition or by employing various TEM$_{n,m}$ cavity modes. The atomic transition was selected by the polarization of a probe laser for cavity transmission measurement while single atoms dropped from a MOT just above the cavity were traversing the cavity.[2] So far, we have realized the coupling constant down to $g = 0.76g_0$. We plan to investigate the atom-cavity system across the EP condition($g_{EP} = 0.5g_0$) by employing high-order TEM modes.

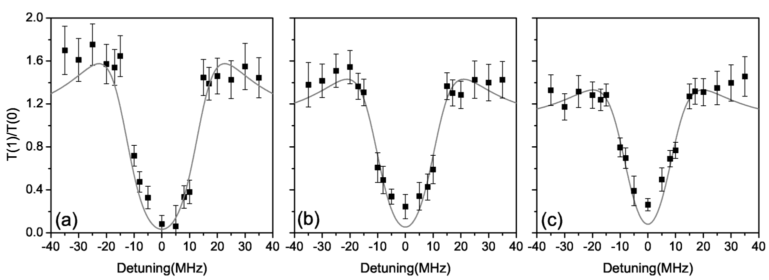

Figure 1: *Transmittance of a cavity coupled with a single rubidium atom. (a) With TEM$_{00}$ mode and σ^+ polarization for the probe. Coupling constant takes a maximum value, $g = g_0$. (b) TEM$_{10}$ mode with σ^+ polarization give $g = 0.86g_0$ due to increased mode volume. (c) TEM$_{00}$ with π polarization result in $g = 0.76g_0$ due to decreased transition strength. The transmittance for a single atom $T(1)$ is normalized with respect to the empty cavity transmittance $T(0)$. The sold curves are theoretical predictions without adjustable parameters.*

[1] W. D. Heiss et al., J. Phys. A: Math. Gen., **23** 1167 (1990).
[2] H. Mabuchi et al., Opt. Lett. **21**, 1393 (1996).

Dynamical Casimir Effect for Two Oscillating Mirrors in 3-D

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The generation of photons in a three dimensional rectangular cavity with two moving boundaries is studied by using the Multiple Scale Analysis (MSA). It is shown that number of photons are enhanced for the cavity whose walls oscillate symmetrically with respect to the center of the cavity. The non-stationary Casimir effect is also discussed for the cavity which oscillates as a whole.