Monday Posters

A digital atom interferometer with single particle control

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Coherent control and delocalization of single trapped atoms constitute powerful new resources for quantum technologies. We will report on a single-atom interferometer that uses spin-dependent periodic potentials to coherently split and recombine particles with spatial separations of up to 24 lattice sites, equivalent to more than 10 μm. The interferometer geometry can be reprogrammed in a digital manner by freely assembling basic coherent operations at discrete time intervals; this allowed us to contrast different geometries and to develop a geometrical-analogue of the well-known spin-echo refocusing. We tested the interferometer by probing external potential gradients, achieving with single atoms 5×10^{-4} precision in units of gravitational acceleration g. Furthermore, a novel scheme for spin-dependent optical lattices is presently underway, with which we expect to reach splitting distances of 1 mm.

This coherent control of single-atom wave packets gives us a new way to investigate and exploit interaction effects between atoms; for instance, molecular bound states of two atoms are predicted to occur in quantum walk experiments as a result of matter-wave interference [1].

Reference

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Interferometry with chip based atom lasers

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We report on the implementation of a Bragg-type interferometer operated with a chip-based atom laser for Rubidium ^{87}Rb. With the chip based atom laser we can generate thermal ensemble as well as Bose-Einstein condensates (BEC) [1]. With the help of delta kick cooling [2], implemented via the atom chip, we can further slow down the expansion of thermal and condensed atoms. In addition, the chip allows to transfer atoms in the individual Zeeman states of the two hyperfine ground states, in particular into the non-magnetic state. With this toolbox we could extend the observation of a BEC of only 10000 atoms to macroscopic time scales approaching two seconds. Benefiting form the extended free fall in microgravity we could combine this with an asymmetric Mach-Zehnder type interferometer over hundreds of milliseconds to study the coherence and to analyze the delta kick cooling with the help of the observed interference fringes. This experiment can be considered as a double slit experiment in microgravity. NB: The QUANTUS cooperation comprises the group of C. Lämmerzahl (Univ. Bremen), A. Wicht (FBH), A. Peters (Humboldt Univ. Berlin), T. Hänsch/J. Reichel (MPQ/ENS), K. Sengstock (Univ. Hamburg), R. Walser (TU Darmstadt), and W. P. Schleich (Univ. Ulm).

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Precision interferometry with Bose-Einstein condensates: toward a new measurement of the fine structure constant

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We report progress, both theoretical and experimental, toward an atom interferometric measurement of $\hbar/M_{\mathrm{Yb}}$, from which a value for the fine structure constant may be determined. By using a symmetric, three-arm contrast interferometer in free space many potential sources of systematic error cancel. For part per billion precision, such an interferometer requires two of the arms to be coherently accelerated. Experimental progress includes improved atom cooling efficiency, allowing production of large (~ 2.5×10^5 atom), nearly pure condensates of ^{174}Yb and faster cycle times for a low-momentum prototype interferometer. Theoretical progress includes new techniques for predicting mean-field effects for all interaction strengths, including the intermediate strength regime which is key to precision BEC interferometry [1]. These techniques are also valid for waveguide interferometers. A comparison of various coherent acceleration schemes will also be presented.

Reference

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Quantum feedback control of atomic coherent states

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Quantum superposition states are under constant threat to decohere by the interaction with their environment. Active feedback control can protect quantum systems against decoherence, but faces the problem that the measurement process itself can change thequantum system. The adaptation of the measurement strategy to a given stabilization goal is therefore an essential step to implement quantum feedback control. Here, we present the protection of a collective internal state of an atomic ensemble against a simple decoherence model. A coherent spin state is prepared and exposed to a noise which randomly rotates the state on the Bloch sphere. We use weak nondestructive measurements with negligible projection of the atomic state which still give sufficient information to apply feedback. This method is used to increase the coherence lifetime of the initial superposition state by about one order of magnitude.

A novel cavity-based atom interferometer

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The world's leading atom interferometers are housed in bulky atomic fountains. They employ a variety of techniques to increase the spatial separation between atomic clouds including high order Bragg diffraction. The largest momentum transfer in a single Bragg beamsplitter has been limited to 24 $\hbar k$ by laser power and beam quality [1]. We present an atom interferometer in a 40 cm optical cavity to enhance the available laser power, minimize wavefront distortions, and control other systematic effects symptomatic to atomic fountains. We expect to achieve spatial separations between atomic trajectories comparable to larger scale fountains within a more compact device. We report on progress in developing this new interferometer using cold Cs atoms and discuss its prospects for exploring large momentum transfer up to 100 $\hbar k$ in a single Bragg diffraction process. The compact design will enable the first demonstration of the gravitostatic Aharonov-Bohm effect [2].

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Coherent population transfer of cold ^{87}Rb atoms by counter-intuitive light pulses

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We consider counter-intuitive light pulses to transfer atoms coherently from the ground state to another ground state through the common excited state, lambda-type configuration [1]. We initially prepared field free cold ^{87}Rb atoms in the ground state of $5S_{1/2}$(F=1). And we detected the fluorescence by atoms in another ground state, $5S_{1/2}$(F=2), to measure amount of transferred atoms. We optimized experimental parameters - width of pulses, power of each pulse, delay time between two pulses, and the two photon detuning- until the effective Rabi frequency of overlapped area of two pulses corresponds to π which means total transfer.

Reference

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Quantum Ramsey interferometry

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The measurement of atomic transition frequencies with Ramsey interferometry has been established as an important tool, not only for general spectroscopic purposes but also to determine frequency standards on which atomic clocks are based on. Improvements of Ramsey interferometry via quantum effects are therefore highly desirable. Here we present methods for quantum enhanced Ramsey-type interferometry using trapped ions or neutral atoms which employ highly non-classical probe-states and decoherence free subspaces [1]. Our methods drastically improve the measurement uncertainty beyond what is possible classically in the presence of experimental noise and tolerate faulty detection and significantly imperfect state preparation. They are therefore feasible with current experimental technology and can lead to improved spectroscopic methods with important applications in metrology.

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The generation of entangled matter waves

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The concept of entanglement has evolved from a controversial building block of quantum mechanics to the basic principle of many highly topical applications. In optics, parametric down-conversion in nonlinear crystals has become one of the standard methods to generate entangled states of light. Bose-Einstein condensates of atoms with non-zero spin provide a mechanism analogous to parametric down-conversion. The presented process acts as a two-mode parametric amplifier and generates two clouds with opposite spin orientation consisting of the same number of atoms. At a total of 10000 atoms, we observe a squeezing of the number difference of -7 dB below shot noise, including all noise sources [1]. As a first application, we demonstrate that the created state is useful for precision interferometry. We show that its interferometric sensitivity beats the standard quantum limit, the ultimate limit of unentangled states.

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An optical ionizing time-domain matter-wave interferometer

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We discuss an all-optical Talbot-Lau interferometer for nanoparticles which consists of 3 pulsed VUV laser gratings [1]. The short laser pulse duration of about 7 ns allows us to address the particles in the time domain, which is a new concept for interferometry of complex matter. The interferometer uses pulsed standing laser light waves as diffracting structures. The light pulses can act as absorptive gratings for matter waves, as soon as the wavelength and laser intensity suffice to photo-ionize each particle with almost certainty in the vicinity of an anti-node of the standing light wave. In contrast to material masks, such gratings can be operated in a pulsed mode, which makes the motion of the particles negligible, in many cases. This establishes a new kind of velocity independent interferometer for molecules and clusters, which has the potential to interfere particles up to 10^6amu and more. This will be relevant for testing spontaneous quantum localization models [2].

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High-sensitivity large area atomic gyroscope

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SYRTE has previously built and extensively characterized a six-axis atom inertial sensor [1,2]. In particular, the uses of a four pulse sequence gyroscope and large momentum transfer beam splitter to enhance its area were investigated [3]. A new interferometer has now been developed at SYRTE based on these study, allowing a 300-fold increased area and enhanced scaling to the rotation; it should in addition allow for more robust large momentum transfer. Details of the architecture and preliminary characterizations will be presented. This very high sensitivity opens important perspectives in particular for fundamental physics, allowing for example improved tests of atom neutrality.

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Design of novel cold atom gravimeter integrated on chip and study of its theoretical performances

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We propose a new design of a cold atom gravimeter integrated on chip. The chosen architecture of the sensor is to first manipulate coherently the internal states of the atoms, the ground-state hyperfine levels | F=1,m_F = -1> and | F=2,m_F = 1>, than to use microwave near-fields on atom chip to generate state-depend potentials. This technique was demonstrated with a Bose-Einstein Condensate (BEC) [1] might be applied also to thermal atoms which will cut-down atoms interactions. Above all, it reduces the detection to simple measures of fluorescence, more effective than imaging techniques. We have studied theoretically the various physical factors limiting the ultimate performances of such an inertial sensor and we propose to demonstrate soon an experimental proof of principle.

Reference

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Suppression of the blackbody radiation shift in atomic clocks

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We develop a concept of atomic clocks where the blackbody radiation shift and its fluctuations can be suppressed by 1-3 orders of magnitude independent of the environmental temperature. The suppression is based on the fact that in a system with two accessible clock transitions (with frequencies ν_1 and ν_2) which are exposed to the same thermal environment, there exists a "synthetic" frequency $\nu_{syn} \propto (\nu_1 - \varepsilon_{12}\nu_2)$ largely immune to the blackbody radiation shift. For example, in the case of $^{171}Yb^+$ it is possible to create a synthetic-frequency-based clock in which the fractional blackbody radiation shift can be suppressed to the level of 10^{-18} in a broad interval near room temperature (300 ± 15 K). We also propose a realization of our method with the use of an optical frequency comb generator stabilized to both frequencies ν_1 and ν_2, where the frequency ν_{syn} is generated as one of the components of the comb spectrum. The work was supported by QUEST, DFG/RFBR (10-02-91335), RFBR (10-02-00406, 11-02-00775, 11-02-01240), Minobrnauka (GK 16.740.11.0466), RAS, Presidium of the SB RAS. D.V.B. was also supported by the Presidential Grant (MK-3372.2012.2).

Magic radio-frequency dressing of nuclear spins in optical atomic clocks

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We investigate the radio-frequency quantum engineering of nuclear spins for an ultra narrow optical clock transition based on the fermionic ^{87}Sr, ^{171}Yb and ^{199}Hg species. A Zeeman-insensitive optical clock transition is produced by dressing nuclear quantum spin with a non resonant radio-frequency (r.f.) field. Particular ratios between the r.f. driving amplitude and the non resonant r.f. field lead to "magic" weak values of the static field where a net cancelation of the differential Zeeman shift with a 100 % reduction of first order fluctuation are observed within a relative uncertainty below 10^{-18} level.

Atomic clocks Mo-014

Optical pumping and spin polarisation in a Cs atomic fountain

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We present a detailed study of optical pumping in a freely evolving cloud of cold Cs atoms launched in an atomic fountain. With π-polarised pumping light tuned to an $F \rightarrow F' = F$ transition, a high degree of atomic spin polarisation was achieved by accumulation of the population in the $m_F = 0$ sublevel of the ground state. Such a scheme has been proposed and demonstrated for thermal beam clocks [1], but the technique has not been widely implemented for normal operation. In the case of cold atoms the random scattering of photons associated with optical pumping significantly increases the temperature of the atomic ensemble. We have investigated theoretically and experimentally the dynamics of the pumping process and the related heating mechanism and considered factors limiting the achievable spin polarisation. This technique has been implemented in a Cs fountain clock, giving a nearly five-fold increase in the useful cold atom signal.

Reference

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A mobile atomic frequency standard with cold atoms

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We have constructed a compact frequency standard using an intra-cavity sample cold cesium atoms. The results show the potential use of clocks with this operation if compared to a cesium beam standard, since all the steps are sequentially performed in the same position of space. Due to the fact that the atomic standard is based on an expanding cloud of atoms, it has no stringent size limitations and one can imagine the possibility of a clock even more compact. For the next step of our ongoing project we are developing a system containing all the laser sources, microwave source and cavity in a single metallic block. The mobile atomic standard based on cold atoms can be an important contribution to a primary standard of high relevance, and a possible strategic product with a broad range of applications.

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Laser excitation of 8-eV electronic states in Th⁺: a first pillar of the electronic bridge toward excitation of the Th-229 nucleus

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The possibility to realize a nuclear clock based on laser excitation of the isomeric state in Th-229 [1,2] has motivated experiments with thorium ions in solids and in ion traps. To facilitate the search for the nuclear transition within a wide uncertainty range about 8 eV, we investigate two-photon excitation in the dense electronic level structure of Th^+, which enables the nuclear excitation via a resonantly enhanced electronic bridge process [3]. In our experiment, the Th^+ resonance line at 402 nm from the $(6d^27s)J$=3/2 ground state to the $(6d7s7p)J$=5/2 state is driven as the first excitation step [4]. Using nanosecond laser pulses in the 250-nm wavelength range for the second step of a two-photon excitation, we have observed several previously unknown levels of Th^+ around 8 eV.

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Portable frequency standard with strontium in optical lattices

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The unprecedented accuracy in time promises new applications like relativistic geodesy for exploration of oil and minerals, fundamental tests of general relativity and synchronization for long base line astronomical interferometry. In fact very recently, space has also opened up as a new avenue for precision measurements based on cold atoms. We are setting up a mobile frequency standard based on strontium (Sr) in a blue detuned optical lattice. We have a 2D-3D MOT (magneto-optical trap) setup where initially cooled atoms in 2D are collected in the 3D MOT. Very recently we have observed an effect of our 2D MOT on our 3D MOT where atom number increases approximately by a factor of 10. However, these are only preliminary results and a thorough optimization as well as characterization will be done in due course of time. An up to date progress on our activities will be presented.

Atomic clocks Mo-018

A neutral mercury optical lattice clock

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Optical lattice clocks [1] are among the most accurate clocks to date and have a huge potential for further improvement, owing to their unique possibility to combine the advantage of the Lamb-Dicke regime spectroscopy (drastic reduction of shifts associated with the dynamics of external variables) together with the possibility of probe a large number of quantum absorbers simultaneously. Among atoms studied in optical lattice clocks, mercury has very low sensitivity to blackbody radiation, making it an excellent candidate for achieving accuracies in the low 10^{-18}, for testing the stability of natural constants or for demonstrating new applications, such as relativistic geodesy. We will report on our first and so far only operation of an Hg optical lattice clock. This includes the first experimental determination of the magic wavelength [2] and the first absolute frequency measurements down to the mid-10^{-15} range [3]. These results demonstrate that the considerable challenge due to the need for deep-UV laser light can be met to make a new clock with extreme accuracy.

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^{87}Sr lattice clock as a reference for the characterization of a Ca^{+} ion clock

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Instability and systematic shifts of optical clocks are rapidly evaluated by referring another stable optical clock. Following an all-optical frequency comparison of two remote ^{87}Sr lattice clocks (one at NICT and the other in University of Tokyo) in 10^{-16} level [1], we conducted an in-laboratory frequency comparison between a single calcium ion clock and the ^{87}Sr lattice clock. The ^{87}Sr lattice clock in NICT has total systematic uncertainty of 5×10^{-16} and the stability reaches 5×10^{-16} in 1000 s. Thus the lattice clock worked as an optical frequency reference for the evaluation of our lately improved Ca^{+} clock, which currently equips a magnetic shield to reduce Zeeman shift [2]. The frequency ratio of $f\,(\mathrm{Ca}^{+})\,/\,f\,(\mathrm{Sr})$ obtained with the optical comparison has statistical uncertainty of 1×10^{-15} in 1000 s and is consistent with separate absolute frequency measurements based on International Atomic Time, where the 10^{-15} level of calibration is notified after a month's latency.

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Precise measurement of vibrational frequencies of ^{174}Yb^{6}Li molecules in an optical lattice; toward the test of variance in m_p/m_e

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Transition frequencies of cold molecules must be accurately evaluated to test the variance in the proton-to-electron mass ratio. Measurement of the $X^2\Sigma\ (v,N) = (0,0)$-> (1,0),(2,0),(3,0),(4,0) transition frequencies of optically trapped ^{174}Yb^{6}Li molecules are the promising method to achieve this goal [1]. ^{174}Yb^{6}Li molecules are produced via Feshbach resonance or optical association, and forced to the $(v,N) = (0,0)$ state by stimulated Raman transition. The Stark shift induced by trap laser is eliminated by choosing appropriate frequencies (magic frequency). For ^{174}Yb^{6}Li molecule, the magic frequency exists also in the far-off resonant area. Using this magic frequency, the Stark shift is less than 10^{-16} if the trap laser frequency is detuned from the magic frequency with 1 MHz. The transition is observed by Raman transition, using two lasers. Also the Stark shift induced by Raman lasers can be eliminated, because the Stark shifts induced by two Raman lasers cancel each other, when the magic frequency exists between both Raman laser frequecnies.

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Phase noise of an atom interferometer for equivalence principle test in space

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High precision cold atom interferometers have important applications in many fundamental physics experiments[1]. Using dual-species atom interferometers to measure the gravity synchronously can make a precision test of the weak equivalence principle. Because ^{85}Rb and ^{87}Rb atoms have similar Raman laser wave vectors, many fluctuations and systematic errors can be eliminated in differential measurement. At the microgravity environment in space, the free evolution time can be greatly extended[2]. We analyze the differential phase noise of an ^{85}Rb-^{87}Rb dual specie atom interferometer in space environment in detail, and find that in typical experimental parameters, $\sigma_\eta=3.2\times10^{-13}$ could be reached per shot, and $\sigma_\eta=3.4\times10^{-15}$ after one day's integration.

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Towards realization of the E-P-R experiment for atoms created via molecular dissociation in pulsed supersonic beam

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An idea of realization of the Einstein-Podolsky-Rosen experiment for two spin-1/2 ^{111}Cd atoms will be presented. The concept is based on the proposal of Fry *et al.* formulated for ^{199}Hg [1]. In the presented experiment, the $^{111}Cd_2$ molecules are produced in a pulsed supersonic beam. Next, the $^{111}Cd_2$ molecules are irradiated by two laser pulses and dissociated in a process of stimulated Raman passage. As a result, two entangled ^{111}Cd atoms with anti-parallel nuclear spins are produced. Orientation of the nuclear spins is recorded using spin-state-selective two-photon excitation-ionization method [2]. Current status of the preparation stage of the experiment will be reported. The project is financed by the National Science Centre (contract UMO-2011/01/B/ST2/00495).

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High precision atomic gravimetry with Bragg-based beam splitters

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We present a gravimeter based on the use of Bragg diffraction to drive atomic beam splitters and mirrors. Traditionally, gravimeters based on cold atoms have used Raman transitions for the optical elements, a process that drives transitions between internal atomic states which are highly sensitive to environmental perturbations (e.g. see [1,2]).Here we show that atoms extracted from a magneto-optical trap with an accelerating optical lattice are a suitable source for a Bragg interferometer, allowing efficient beam splitting and separation of momentum states for detection. Our current device, based on a $T = 60$ms, $4\hbar k$ interferometer, achieves a sensitivity of $\Delta g/g$ of 2×10^{-9} in 15 minutes. We discuss a number of improvements which should push this device into the μGal regime and beyond.

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Thermal effects in the Casimir-Polder interaction

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The long-range atom-surface interaction, of Casimir-Polder type, is a fundamental interaction, which modifies the electrodynamics corrections of atomic energy levels, as due to limiting conditions imposed by the surface. The realm of non-zero temperature corrections, which can be interpreted as a coupling of an atomic detector with the near-field of a blackbody radiator, has received little experimental attention, In the achievement of [1], a key point allowing the observation, was an amplification, in a long-distance situation, of thermal effects by a non-equilibrium situation (overheated surface, relatively to the remote environment). We are presently performing experiments at Cs(7D)/saphir interface in the near-field regime, and observe an increase of the atom-surface attraction with the temperature of equilibrium. We show also that in this near-field regime, a thermal disequilibrium does not amplify the interaction, solely governed by the surface temperature.

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The *g*-factor of hydrogen- and lithiumlike silicon

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Ultra-precise measurements of the gyromagnetic factor (*g*-factor) of a bound electron in highly charged medium-heavy ions provide a sensitive test of quantum electrodynamics in bound systems (BS-QED) under extreme conditions. To determine the *g*-factor the Larmor frequency and the free cyclotron frequency of a single ion are measured in a triple Penning-trap setup. The continuous Stern-Gerlach effect allows an indirect measurement of the Larmor frequency. The free cyclotron frequency is determined by the measurement of the three motional eigenfrequencies. In this context the *g*-factor of hydrogenlike silicon $^{28}Si^{13+}$ has been measured with a relative uncertainty of $5 \cdot 10^{-10}$ representing the most stringent test of BS-QED in strong fields [1]. Two *g*-factor measurements of a hydrogenlike and a lithiumlike system with the same nucleus offer a test of the electron-electron interaction calculations. For this reason the *g*-factor measurementof $^{28}Si^{11+}$ is currently under progress. The measurement procedure and results are presented.

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New perspectives on the search for a parity violation effect in chiral molecules

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Parity violation (PV) effects have so far never been observed in chiral molecules. Originating from the weak interaction, PV should lead to frequency differences in the rovibrational spectra of the two enantiomers of a chiral molecule. However the weakness of the effect represents a very difficult experimental challenge. We propose to compare the rovibrational spectra (around 10 μm) of two enantiomers, recorded using the ultra-high resolution spectroscopy technique of Doppler-free two-photon Ramsey fringes in a supersonic molecular beam. With an alternate beam of left- and right-handed molecules and thanks to our expertise in the control of the absolute frequency of the probe CO_2 lasers, we should reach a fractional sensitivity better than 10^{-15}, on the frequency difference between enantiomers [1].

We will review our latest results on the high-resolution spectroscopy, either in cell or in a supersonic beam, of methyltrioxorhenium [2], an achiral test molecule from which our collaborators are currently synthesizing chiral derivatives fulfilling all the requirements for the PV test.

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Heralded entanglement between widely separated atoms

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Entanglement is the essential feature of quantum mechanics. Its importance arises from the fact that observers of two or more entangled particles will find correlations in their measurement results, which can not be explained by classical statistics. In order to make it a useful resource for, e.g., scalable long-distance quantum communication, heralded entanglement between distant massive quantum systems is necessary. Here we report on the generation and analysis of heralded entanglement between spins of two single Rb-87 atoms trapped independently 20 meters apart [1]. We observe an entanglement fidelity of 0.82 which is high enough to even violate a Bell inequality. This achievement together with our recently developed ultra-fast and highly efficient single atom detector [2] form the starting point for new experiments in quantum information science and for a first loophole-free test of Bell's inequality [3,4].

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Mo-028 Precision measurements…

Determination of the fine structure constant and test of the quantum electrodynamics

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We present a measurement of the ratio h/m_{Rb} between the Planck constant and the mass of ^{87}Rb atom using atom interferometry. A new value of the fine structure constant, with a relative uncertainty of 6.6×10^{-10}, is deduced[1]: α^{-1} = 137.035 999 037 (91). Using this determination, we obtain a theoretical value of the electron anomaly a_e = 0.001 159 652 181 13 (84) which is in agreement with the experimental measurement of Gabrielse (a_e = 0.001 159 652 180 73 (28)). The comparison of these values provides the most stringent test of the QED. Moreover, the precision is large enough to verify for the first time the muonic and hadronic contributions to this anomaly.

Using this method, it seams possible to further reduce systematic effects and improve the precision of the measurement by a factor 7.

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Development of a double MOT system and spectroscopy of iodine molecule at 718 nm toward the electron EDM measurement

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Search for the permanent electric dipole moment (EDM) of the elementary particles has been of considerable interest in the recent decades. Laser cooling and trapping technique reduces the systematic error of the EDM measurement due to the $v \times E$ effect. Further, it dramatically elongates the interaction time with an external electric field by two or three orders of magnitude, when compared to the conventional atomic beam experiments. This longer interaction time substantially improves the sensitivity of the EDM measurement. Additionally, Francium (Fr) being the heaviest alkali atom has a large enhancement factor of about 900. The laser cooled Fr atoms are promising for the measurement of the e-EDM. As the Fr production requires the cyclotron operation which being expensive for a continuos operation, we work with Rb atoms and the Rb beam is utilized for optimizing the operation parameters of the entire apparatus. We have developed a double magneto-optical trap (MOT) system and trapped Rb atoms. We have also observed the saturated absorption spectra of iodine molecules at 718 nm. The high resolution signal is used to stabilize the laser frequency to the D2 transition of Fr atom.

Direct measurement of the proton magnetic moment

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We report the first direct measurement of the proton magnetic moment at the part per million level [1]. Using a single proton in a Penning trap, this demonstrates the first method that should work as well with an antiproton ($\bar{p}$) as with a proton (p). This opens the way to measuring the $\bar{p}$ magnetic moment (whose uncertainty has essentially not been reduced for 20 years) at least 10^3 times more precisely.

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Intracavity two-photon spectroscopy and a potential hand-size secondary frequency standard

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We report an intracavity scheme for diode laser based two-photon spectroscopy [1]. To demonstrate generality, three ^{133}Cs hyperfine transition groups of different wavelengths are shown. For the 6S-6D transitions, we achieved 10^2 times better signal-to-noise ratio than previous work[1] with 10^{-3} times less laser power, revealing some previously vague and unobserved spectra. Possible mutual influences between the two-photon absorber and laser cavity were investigated for the first time to our knowledge, which leads to the application of a reliable and hand-sized optical frequency reference. Our approach is applicable for most of the two-photon spectroscopy of alkali atoms. We currently measured the absolute frequencies of all the two-photon hyperfine transitions. The reproducibility of measured frequencies (within 3 kHz, two months) is encouraging for considering the application of our scheme to be a hand-size diode-laser based secondary frequency standard.

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Towards the absolute calibration of the reference line for muonium 1S-2S spectroscopy

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A muonium atom (*Mu*) is a bound state formed by a muon (μ^+) and an electron, offering a structureless two-body leptonic system whose energies can be evaluated with high accuracies by the bound-state QED. The $1S-2S$ transition of *Mu* is of particular importance because the muon mass and the ground-state Lamb shift contribution can be derived from it imposing a cross-check on the recent muonic hydrogen $2S-2P$ Lamb shift measurement in which a smaller than expected proton size was found [1]. The current experimental resolution of $Mu\ \Delta\nu_{1S-2S}$ is limited by (a) the flux of *Mu* in vacuum, (b) the frequency chirps in the pulsed light source, and (c) the precision of the reference line. In this conference, we present our effort in improving the precision of the 732 nm reference line in molecular iodine that is suitable for the $Mu\ \Delta\nu_{1S-2S}$ spectroscopy.

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Imaging the build-up of a quantum interference pattern of massive molecules

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New experiments allow us for the first time to visualize the gradual emergence of a deterministic far-field matter-wave diffraction pattern from stochastically arriving single molecules. A slow molecular beam is created via laser evaporation of the molecules from a glass window. The molecules traverse an ultra-thin nanomachined grating at which they are diffracted and quantum delocalized to more than 100 µm before they are captured on a quartz plate at the interface between the vacuum chamber and a self-built fluorescence microscope. Fluorescence imaging provides us with single molecule sensitivity and we can determine the position of each molecule with an accuracy of 10 nm. This new setup is a textbook demonstration but it also enables quantitative explorations of the van der Waals forces between molecules and material gratings. An extrapolation of our present experiments to even thinner gratings is expected to also enlarge the range of nanoparticles that are accessible to advanced quantum experiments.

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Electric dipole moments and parity violation in atoms and molecules

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This presentation is based on the following recent publications [1, 2, 3, 4, 5]:

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Precision magnetometry with spin-polarized xenon: toward a Neutron EDM Co-magnetometer

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Atomic magnetometer sensitivity is a limiting factor in precision measurements, medical imaging, and industrial applications. In particular, searches for permanent electric dipole moments (EDMs) require sensitive magnetometers which interact minimally with the primary samples. Techniques based on spin-polarized gases have been very successful in this capacity, but it remains difficult to perform correct spatial and temporal averages. Previous magnetometers (e.g. alkalis or ^{199}Hg) also suffer from material problems at the high voltages and low temperatures common in EDM experiments. We propose as a remedy real-time optical magnetometry based on spectroscopy of two-photon transitions in spin-polarized ^{129}Xe. Thermal, diffusive, and dielectric properties of xenon allow sensitive measurements in a wide range of electromagnetic field strengths and sample volumes, while long spin coherence times and a low neutron capture cross-section are favorable in neutron EDM experiments. We report on preliminary work validating the technique in ^{171}Yb and a parallel effort measuring the ^{129}Xe EDM, and survey applications to contemporary neutron EDM measurements.

Large scale CIV3 calculations of fine-structure energy levels and lifetimes in co XIV

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Large scale CIV3 calculations of excitation energies from ground state 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 $(1s^2 2s^2 2p^6)3s^2 3p^2$, $3s3p^3$, $3p^4$, $3s^2 3p3d$, $3p^3 3d$, $3s3p3d^2$, $3s^2 3d^2$, $3s3p^2 3d$, $3s3p^2 4s$, $3s^2 3p4s$, $3s^2 3p4p$, $3s^2 3p4d$ and $3s^2 3p4f$ configurations of Co XIV, are performed using very extensive configuration-interaction (CI) wavefunctions. The relativistic effects in intermediate coupling are incorporated by means of the Breit-Pauli Hamiltonian. Our calculated excitation energies and the radiative lifetimes of the fine-structure levels are in excellent agreement with the data compiled by NIST and the experimental lifetimes, wherever available.

Relativistic effects on the hyperfine structures of $2p^4(^3P)3p\ ^2D^o$, $^4D^o$, $^2P^o$ in F I

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In this work, the hyperfine interaction constants of the $2p^4(^3P)3p\ ^2D^o$, $^4D^o$ and $^2P^o$ levels in neutral fluorine are investigated theoretically. Large-scale calculations are carried out using the atsp2k [1] and grasp2k [2] packages based on the multiconfiguration Hartree-Fock (MCHF) and Dirac-Fock (MCDF) methods, respectively. In both non-relativistic and relativistic models, the set of many-electron states selected to form the total wave function is constructed systematically using the "single and double multireference" approach. In the framework of MCHF, the relativistic effects are taken into account, either in the Breit-Pauli (BP) approximation using the MCHF orbitals or through relativistic configuration interaction (RCI) calculations, in which the non-relativistic one-electron basis is converted to Dirac spinors using the Pauli approximation [3]. The MCHF-BP, RCI and MCDF results are in satisfactory agreement with experiments, but differ from the MCHF calculations. It shows that, in a system like F I, relativistic effects can be crucial but do not require the use of a fully relativistic method.

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Spectroscopy Mo-038

Dual frequency comb spectroscopy in the near IR

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We use two Er^+ fiber lasers with slightly different repetition rates to perform a modern type of Fourier transform spectroscopy without moving parts [1]. The measurements are done in real time and take less than 100μs to record an interferogram. We work with two femtosecond Er^+fiber lasers with somewhat different spectral outputs and employ spectral filtering based on a grating setup to select the common spectral region of interest from the two lasers, thereby increasing the signal to noise ratio. The interferogram is taken with a 20 cm long gas cell, containing a mixture of acetylene and air at atmospheric pressure, and is fast-Fourier-transformed to obtain the spectrum. Dual comb spectroscopy has the multiplex advantages over other comb spectroscopies [2]; it requires only a single fast photodiode (and not a CCD array) and enables acquiring spectra in real time. We acknowledge Qatar Foundation, NPRP grant 09 - 585 - 1 – 087 and the NSF grant No. 1058510.

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Theoretical and experimental study of polarization self-rotation for Doppler-broadened rubidium atoms

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We present a theoretical and experimental study of polarization self-rotation of an elliptically polarized light for a Doppler-broadened rubidium atomic cell. The accurate density matrix equations are solved numerically as a function of velocity and elapsed time. Then, the density matrix elements are averaged over atomic transit times and a Maxwell-Boltzmann velocity distribution. We calculate the rotation angle as a function of detuning for various laser intensities and polarizations, and compare the calculated results with experimental results.

Observation of enhanced transparency by using coherent population trapping than typical EIT system in the Rb cell

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We observed high contrast transparency signal in the Rb cell with the buffer gas, 50 torr Ne. We used phase matched two co-propagating lasers (CPT laser) which have linearly orthogonal polarization to make CPT state. And the two lasers which have 6.8 GHz frequency difference corresponds hyperfine splitting of ^{87}Rb make λ-type configuration. Another weak laser which is co-propagating with CPT lasers makes λ-type configuration with a CPT laser and I-type configuration with another CPT laser, simultaneously. We observed three times enhanced transparency signal with three lasers than typical λ-type EIT (electromagnetically induced transparency) signal. We can also observe that the transparency signal has more slow decay shape near resonant region due to more decay channels.

Nonlinearly optical generation of atomic dispersive lineshape to laser frequency stabilization

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Avoiding laser frequency drifts is a key issue in many atomic physics experiments. Techniques usually involve either the generation of dispersive atomic lineshapes through frequency modulation of absorptive lines or using differential magnetic shifts of Zeeman sub-levels. Here we describe a simple and robust technique to lock the laser frequency using nonlinear properties of an atomic vapor to produce the dispersive signal [1]. The atomic vapor behaves like a Kerr medium exhibiting self-focusing/-defocusing behavior depending on which side of the resonance the laser frequency is, thus modifying the beam power transmitted through an aperture after the vapor cell. Scanning the frequency across resonance thus results in a dispersive lineshape that can be used as an error signal to lock the laser frequency. This technique exhibits performance similar to usual ones with the advantage of not needing modulation or the use of magnetic fields to be performed.

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Singlet-state spectroscopy of the negatively charged nitrogen-vacancy center in diamond

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The nitrogen-vacancy (NV) color center in diamond consists of a substitutional nitrogen atom in the diamond lattice adjacent to a missing carbon atom (a vacancy). The ground state of the negatively charged NV^- center can be optically spin-polarized and has a long transverse spin relaxation time, which makes it useful for applications such as electric and magnetic field sensing, sub-diffraction-limited imaging, and quantum information. Despite the recent interest in developing these applications, our understanding of the NV^- basic properties is incomplete. Theoretical models disagree on the details of the NV^- energy level structure and predict additional energy states that have not been observed. We have performed broadband absorption spectroscopy out of the metastable ^1E NV^- state in search of previously unobserved states and to study the 1042 nm singlet-singlet phonon sideband. Our findings provide insight on how NV^- singlet states are coupled to phonons and shed light on the energy level structure and optical pumping mechanism.

Photoionization microscopy

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The principle of photoionization microscopy has been known since the early 80's [1]. In theory it should allow for direct observation one of the most elusive quantum objects - the wave function. Nearly three decades later, with the emergency of the velocity map imaging technique [2], we present an experimental proof of this statement. In our experiment atomic hydrogen is photoexcited into high lying Stark states. The presence of a dc electric field ensures lowering of the potential barrier and leads to autoionization. The ionized electrons are projected on a detector, where they create interference rings due to the existence of different trajectories to the detector. The number of dark fringes equals the parabolic quantum number n_1: the number of nodes of the electronic wave function along the ξ coordinate. By counting these minima we can immediately identify the Stark states. Our experimental findings agree with quantum calculations based on wavepacket propagation.

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Photon recoil heating spectroscopy of metal ions

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Many atoms and molecules with interesting spectroscopic properties can not be laser cooled owing to their complex internal level structure. We present a universal spectroscopy system based on sympathetic cooling of a spectroscopy ion through a co-trapped logic ion which is laser cooled [1]. Spectroscopy is performed by monitoring the effect of photon recoil on the motional state of the two-ion crystal. Starting from the motional ground state, scattering of photons near the resonance of a spectroscopy transition leads to photon recoil heating which can be detected efficiently on the logic ion [2]. This allows us to detect the scattering of only 60 photons using a Ca^+ spectroscopy and Mg^+ logic ion. The use of non-classical motional states to enhance the sensitivity will be discussed. The setup is versatile and will allow performing precision spectroscopy of other metal ions relevant to the search for a possible variation of the fine-structure constant using quasar absorption spectroscopy.

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Experimental techniques for studying two-dimensional quantum turbulence in highly oblate Bose-Einstein condensates

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We have developed a collection of techniques for generating large disordered distributions of quantized vortices in highly oblate Bose-Einstein condensates (BECs) for studies of two-dimensional quantum turbulence. In our experimental approach, we generateturbulent states by exciting the condensate either through modulating the trapping magnetic field, or through stirring or swiping the BEC with a blue-detuned laser beam. Additionally, we are developing methods for building up vortex distributions core bycore with control over winding number and vortex positions. These vortex manipulation techniques will allow us to study the vortex dynamics and interactions that are involved in two-dimensional quantum turbulence.

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Beliaev theory of spinor Bose-Einstein condensates

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By generalizing the Green's function approach proposed by Beliaev [1, 2], we investigate the effect of quantum depletion on the energy spectra of elementary excitations in an F = 1 spinor Bose-Einstein condensate, in particular, of ^{87}Rb atoms in an external magnetic field. We find that quantum depletion increases the effective mass of magnons in the spin-wave excitations with quadratic dispersion relations. The enhancement factor turns out to be the same for both ferromagnetic and polar phases, and also independent of the magnitude of the external magnetic field. The lifetime of these magnons in a ^{87}Rb spinor BEC is shown to be much longer than that of phonons. We propose an experimental setup to measure the effective mass of these magnons in a spinor Bose gas by exploiting the effect of a nonlinear dispersion relation on the spatial expansion of a wave packet of transverse magnetization. This type of measurement has practical applications, for example, in precision magnetometry.

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Trap loss of ultracold metastable helium: non-exponential one-body loss and magnetic-field-dependent two- and three-body loss

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We have experimentally studied the decay of a BEC of metastable ^{4}He atoms in an optical dipole trap, for atoms in the $m = +1$ and $m = -1$ magnetic substates and up to a magnetic field of 450 G [1]. Our measurements confirm long-standing calculations of the two-body loss rate coefficient that show a strong increase above 50 G. We have obtained a three-body loss rate coefficient of $6.5(0.4)_{\text{stat}}(0.6)_{\text{sys}} \times 10^{-27}$ cm^{6}s^{-1}, which is interesting in the context of universal few-body theory.

In the regime where two- and three-body losses can be neglected, the total number of atoms decays exponentially with time constant τ. However, the thermal cloud decays exponentially with time constant $\frac{4}{3}\tau$ and the condensate decays much faster, and non-exponentially [2]. We have observed this behavior [3], which should be present for all BECs in thermal equilibrium with a considerable thermal fraction.

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Quantum criticality of spin-1 bosons in a 1D harmonic trap

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We investigate universal thermodynamics and quantum criticality of spin-1 bosons with strongly repulsive density-density and antiferromagnetic spin-exchange interactions in a one-dimensional harmonic trap. From the equation of state, we find that a partially-polarized core is surrounded by two wings composed of either spin-singlet pairs or a fully spin-aligned Tonks-Girardeau gas depending on the polarization. We describe how the scaling behaviour of density profiles can reveal the universal nature of quantum criticality and map out the quantum phase diagram. We further show that at quantum criticality the dynamical critical exponent $z = 2$ and correlation length exponent. $\nu = 1/2$. This reveals a subtle resemblance to the physics of the spin-1/2 attractive Fermi gas.

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Measurement of momentum distribution of one dimensional quasiBEC using focusing techniques

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We measure the momentum distribution of one-dimensional quasi-BEC using focusing techniques. By varing the temperature and density, the crossover from ideal Bose gas to quasi-condensate is probed. We model our data using a classical field theory [1] and obtain a temperature similar to that extracted from *in situ* density fluctuation measurements [2]. We also compare our results with Quantum Monte Carlo calculations.

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Feshbach spectroscopy of an ultracold ^{85}Rb-^{133}Cs mixture

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Ultracold and quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear ground-state molecules possessing a permanent electric dipole moment. The anisotropic, long range dipole-dipole interactions between such molecules offers many potential applications, including novel schemes for quantum information processing and simulation. Our goal is to create ultracold ground-state RbCs molecules using magneto-association on a Feshbach resonance followed by optical transfer to the rovibronic ground state. The pre-requisite to this approach is the attainment of a high phase space density atomic mixture and the identification of suitable interspecies Feshbach resonances. Here we present the latest results from our experiment, including the realisation of a quantum degenerate mixture of ^{87}Rband ^{133}Cs [1] and a detailed study of the Feshbach spectrum of an ultracold ^{85}Rb–^{133}Cs mixture.

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Quantum tri-criticality and phase transitions in spin-orbit coupled Bose-Einstein condensates

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We consider a spin-orbit coupled configuration of spin-1/2 interacting bosons with equal Rashba and Dresselhaus couplings. The phase diagram of the system at $T = 0$ is discussed with special emphasis to the role of the interaction, treated in the mean-field approximation. For a critical value of the density and of the Raman coupling we predict the occurrence of a characteristic tri-critical point separating the spin mixed, the phase separated and the zero momentum states of the Bose gas. The corresponding quantum phases are investigated analyzing the momentum distribution, the longitudinal and transverse spin-polarization and the emergence of density fringes. The effect of harmonic trapping as well as the role of the breaking of spin symmetry in the interaction Hamiltonian are also discussed.

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Melting of fractional vortex lattice in a rotating spin-1 antiferromagnetic Bose-Einstein condensate at finite temperatures

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The stability of the half-quantized vortex lattice in the rotating spin-1 antiferromagnetic Bose- Einstein condensate [1] is studied at finite temperatures. By solving the stochastic projected Gross- Pitaevskii equation [2], we study how the lattice structures in both superfluid densities and spin texture are distorted and melted at higher temperatures. We find that the half-quantized vortex lattice and the domain wall of the spin texture are vulnerable to the thermal fluctuations. In the typical experiments of spinor BEC, the lowest temperature attainable is about 50 nK [3] which is much higher than that of a scalar BEC. Our investigations simulate the equilibrium configuration of the half-quantized vortex lattice in a rotating spin-1 BEC when thermal fluctuations are important.

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Bose-Einstein condensate in a highly anisotropic dressed quadrupole trap

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We demonstrate the trapping of a ^{87}Rb Bose-Einstein condensate in a very anisotropic radio-frequency (RF) dressed quadrupole trap. The condensate is first produced in a magnetic quadrupole trap plugged in its center by a blue detuned laser, carefully optimized to overcome Majorana losses [1]. Once condensed, the atoms are transferred to the dressed trap by sweeping the RF frequency and removing slowly the plug laser. In the dressed trap, the RF coupling is precisely determined by spectroscopy and the lifetime of the dressed atoms reaches several minutes. The oscillation frequencies are measured for different values of the RF field and magnetic gradient, indicating the achievement of a highly anisotropic trap. For the maximum value of the magnetic gradient, we reach the two-dimensional regime for the degenerate gas.

Our results represent an important step towards the realization of a ring-shape trap [2] where we will investigate the connection between superfluidity and Bose-Einstein condensation in 2D and 3D.

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Quantum and thermal transitions out of the pair-supersolid phase of two-species bosons in lattice

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We investigate two-species bosons in a two-dimensional square lattice by quantum Monte Carlo method. We show that the inter-species attraction and nearest-neighbor intra-species repulsion results in the pair-supersolid phase, where a diagonal solid order coexists with an off-diagonal pair-superfluid order. The quantum and thermal transitions out of the pair-supersolid phase are characterized. It is found that there is a direct first order transition from the pair-supersolid phase to the double-superfluid phase without an intermediate region. Furthermore, the melting of the pair-supersolid occurs in two steps. Upon heating, first the pair-superfluid is destroyed via a Kosterlitz-Thouless transition then the solid order melts via an Ising transition.

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Bose-Einstein condensation in quantum crystals: the quest of supersolidity

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The experimental observation of superfluidity effects in solid ^{4}He at low temperature [1] suggests the existence of a *supersolid* state of matter, i.e. a crystalline phase performing Bose-Einstein condensation (BEC). Although the first conjectures on supersolidity appeared some decades ago, a reliable microscopic model of this phenomenon is still lacking, since it is hard to describe the competing effects of localization, due to the crystalline order, and delocalization, due to the zero-point motion, which characterize the atoms in quantum solids. In this work, we present a microscopic approach to the solid phase of ^{4}He, based on Path Integral Monte Carlo simulations. In particular, we compute the one-body density matrix $\rho_1(r)$ of ^{4}He crystals at different temperatures, in order to study the BEC properties of these systems: we find that perfect crystals do not support BEC at any temperature [2] and that crystals presenting vacancies below a certain temperature become supersolid [3].

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Quantum Monte Carlo study of a resonant Bose-Fermi mixture

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We study resonant Bose-Fermi mixtures at zero temperature, with different relative concentrations of the bosons. We use for the first time a Quantum Monte Carlo method with Fixed-Node approximation, to explore the system from the weak to the strong coupling limit. A repulsive interaction among bosons is introduced to provide stability to the bosonic component. Beyond the unitarity limit, the resonant attractive interaction supports a bound fermionic dimer. At the many-body level, increasing the boson-fermion coupling the system undergoes a quantum phase transition from a state with condensed bosons immersed in a Fermi sea, to a normal Fermi-Fermi mixture of the composite fermions and the bare fermions in excess. We obtain the equation of state and we characterize the momentum distributions both in the weakly and in the strongly interacting limits. We compare QuantumMonte Carlo results to T-matrix calculations, finding interesting signatures of the different many-body ground states.

Non-Abelian spin singlet states of bosons in artificial gauge fields

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Using exact diagonalization we study strongly correlated phases of a two-component Bose gas in an artificial gauge field. The atoms are confined in two dimensions and interact via a two-body contact. We show that for SU(2) symmetric interactions and Abelian gauge fields the correlated nature of the system energetically favors spin singlets. Incompressible phases are formed at fillings $\nu = 2k/3$, for which, in close analogy to the Read-Rezayi (RR) series in spin-polarized systems, a series of non-Abelian spin singlet (NASS) states is known, being the exact zero-energy eigenstates of a $(k + 1)$-body contact interaction. Explicit calculations reveal the relevance of these states also for our system with a realistic two-body interaction. Subjecting the atoms to non-Abelian gauge fields, it becomes possible to switch between RR-like and NASS-like states by varying the non-Abelian gauge field strength.

Confined *p*-band Bose-Einstein condensates

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We study bosonic atoms on the p band of a two-dimensional optical square lattice in the presence of a confining trapping potential. Using a mean-field approach, we show how the anisotropic tunneling for p-band particles affects the cloud of condensed atoms by characterizing the ground-state density and the coherence properties of the atomic states both between sites and atomic flavors. In contrast to the usual results based on the local-density approximation, the atomic density can become anisotropic. This anisotropic effect is especially pronounced in the limit of weak atom-atom interactions and of weak lattice amplitudes, i.e., when the properties of the ground state are mainly driven by the kinetic energies. We also investigate how the trap influences known properties of the non-trapped case. In particular, we focus on the behavior of the antiferromagnetic vortex-antivortex order, which for the confined system is shown to disappear at the edges of the condensed cloud.

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Negative magneto-resistance in disordered ultra-cold atomic gases

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Anderson Localization[1] was first investigated in the context of electrons in solids. One success of Anderson's theory of weak localisation was in explaining the puzzle of negative magneto-resistance[2] – as early as the 1940s it had been observed that electron diffusion rates in some materials can increase with the application of a magnetic field. This is because Anderson Localization is an interference phenomenon and breaking time reversal symmetry through the application of an external magnetic field inhibits that interference. Anderson Localization has already been demonstrated in one dimensional ultra-cold atomic gases[3]. We present a theoretical demonstration of weak localisation in a two-dimensional Bose condensed gas. We then demonstrate that a synthetic magnetic field can be imposed on the gas using the scheme of Spielman[4]. We show that this can lead to both positive and negative magneto-resistance in the gas and provide an in-depth analysis of the resulting phases.

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Faraday imaging of Bose-Einstein condensates

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Faraday rotation has a long and fruitful history in atomic physics and quantum optics. It describes the rotation of the polarization of a light beam as it passes through a medium. The effect has been employed very successfully in atomic gases at room temperature and in laser cooled atomic ensembles, resulting in e.g. squeezing and entanglement of atomic spins and for quantum information protocols.

Here we demonstrate the use of Faraday rotation to non-destructively image ultra cold atomic clouds and Bose-Einstein condensates. We show that dark ground Faraday imaging allows us to take many images of a single ultra cold cloud and present a detailed analysis of the destructiveness. This ability allows us to monitor e.g. the condensation process or the inherent oscillation of these atomic samples in a single experimental realization.

Our experiments are performed with ultra cold ^{87}Rb samples using light at a blue detuning of 0-1.5 GHz from the D2 transition. We present the laser system to generate the off-resonant light and show that we have obtained good quantitative agreement between the observed and predicted Faraday rotation both in room temperature and ultra cold samples.

In the future we will extend this technique to high resolution imaging of atomic samples in optical lattices and to multi component quantum gases. This will allow for probing and control of these systems beyond the quantum noise level.

Ab initio stochastic description of 5 fluctuating quasicondensate experiments

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The proposed modified form of the stochastic Gross-Pitaevskii equation [1] is demonstrated to be an excellent tool for *ab initio* studies of (quasi-)one-dimensional weakly-interacting Bose gases (supplemented here by self-consistent treatment of radially-excited thermal modes). In the regime $\mu < \hbar\omega_\perp$ we show [1] that this model accurately reproduces densities and density fluctuations in atom chip experiments of Bouchoule [2, 3] and van Druten [4]; in the regime $\mu <$ few $\hbar\omega_\perp$ we also demonstrate excellent reconstruction of earlier quasi-one-dimensional phase fluctuation experiments in the group of Alain Aspect (PRL 2003; EPJD 2005). We acknowledge funding from EPSRC (EP/F055935/1).

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Pre-thermalization in an isolated many-body quantum system

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Understanding non-equilibrium processes in many-body quantum systems is an important open problem in physics. We study the relaxation dynamics of a coherently split one-dimensional Bose gas on an atom chip by performing time-resolved measurements of the probability distribution function of matter-wave interferences. After (fast) splitting, the system follows a rapid evolution before reaching a quasi-steady state. This state is characterized by an effective temperature for the condensates relative phase degrees of freedom, which we observe to be independent on the initial temperature of the gas (before splitting) and determined by the atom number fluctuations corresponding to the splitting process. We do not observe the onset of thermalization on the time-scale achievable by our experiment, and associate this relaxation dynamics with the phenomenon of pre-thermalization. We will report our new results for the dynamics of a system with tunnel coupling bewteen the two parts of the split condensate.

Thermodynamic analysis of a trapped BEC using global variables

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Using the concept of global variables to describe the thermodynamic properties of a trapped Bose-Einstein Condensate [1] we have performed two classes of experiments. In a first experiment, a BEC of ^{7}Li held in an optical trap in an almost 1D regime, was employed to explore the contributions of the condensate and the thermal clouds to the overall pressure of the system. Different scattering lengths were considered and we could demonstrate the dominance of the condensate contribution for $T \ll T_c$. In a second experiment, we have used a BEC of ^{87}Rb trapped in a hybrid trap, composed by the combination of a magnetic and an optical trap. In this type of trap it is possible to vary the geometry of the system, going from an almost spherical BEC to a very elongated cigar-shaped one, providing the possibility to study different regimes. One of the studies in progress is the investigation of the thermodynamic transformations of the condensate as well as the determination of the order of the BEC transition for an inhomogeneous trapped gas.

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A 1D Bose gas in a box trap on an atom chip

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Atom chips give promising access to tailored axial potentials for one-dimensional (1D) gases by employing specifically designed wire patterns. The magnetic trapping potential of our chip features a strong harmonic confinement in the radial direction combined with a box-like confinement along the axial direction [1]. The ideal Bose gas behaves rather differently in a box when compared to a harmonic trap [2]. Furthermore, homogeneity of the atomic density along the 1D axis allows a closer comparison to exact theoretical treatments, without the need for the local-density approximation. We characterise the loading of 1D Bose gases near quantum degeneracy in the box trap and the influence of potential roughness on the density distribution. The prospects of reaching the strongly interacting regime by reducing the density are investigated.

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Vortex dipole in a dipolar Bose Einstein condensate

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We studied a single charged quantized vortex dipole in a dipolar Bose Einstein Condensate (BEC) in the Thomas Fermi (TF) limit. We calculated the critical velocity for the formation of a pair of vortices with opposite charge in an oblate dipolar BEC. We made a comparision between the critical velocities of dipolar and nondipolar condensates. The dependence of the critical velocity on the dipolar interaction strength and vortex seperation was discussed. We found that dipolar interactions change the critical velocity of vortex dipole and affect the superfluid properties of BEC.

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A mesoscopic gas of spin 1 bosons

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One of the most active topic in the field of ultra cold quantum gases is the study of interacting many-body systems with spin [1,2]. Atoms with arbitrary Zeeman structure can be trapped by far-detuned optical traps. In our group, we construct an all-optical setup in order to study spin 1 condensates in sodium gases. We achieved to reach Bose-Einstein condensation regime by MOT pre-cooling and two-stages evaporative cooling, with about 5000 atoms. We explore the phase diagram with magnetization and magnetic field at low temperature in equilibrium state. Two phases are found, reflecting a competition between the spin-dependent interaction and the quadratic Zeeman energy. The measurements are in quantitative agreement with mean-field theory and single mode approximation. We also notice an abnormal large fluctuation at small magnetization and low magnetic field, which opens future works for us.

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First and second sound in an ultra-cold Bose gas

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First and second sound are the hallmarks of two-fluid hydrodynamics. These sound modes consist of density and temperature modulations in the non-condensed and condensate fractions of an ultra-cold bosonic gas. There is a coupling between first and second sound, leading to an avoided crossing at a temperature around 0.05 Tc, which has never seen been experimentally. To investigate the dispersion relation of these modes, two approaches are followed. First, a perturbation is made in the potential creating a travelling sound wave[1]. In a second experiment, a standing sound wave is induced by periodically modulating the trapping potential. Using phase-contrast imaging[2] and singular value decomposition, the speed of sound and the dispersion relation are extracted from these experiments.

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Time averaged optical traps with an all optical BEC

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We report on our preliminary results of a toroidal trap for BEC of ^{87}Rb using time averaged optical potentials [1]. Our apparatus consists of a crossed dipole trap formed by two focused beams of 1064 nm light overlapping in the horizontal plane. Atoms are initially loaded to a single beam dipole trap from a standard 3D-MOT. Evaporative cooling is first performed in the single beam trap, followed by compression and additional confinement with a second orthogonal beam [2]. We achieve nearly pure condensates of 10^4 atoms in the $F=1$ ground state. Spin state selection is achieved via application of magnetic gradients during the evaporation. The toroidal trap is formed from a third beam in the vertical direction that is scanned by a 2D AOM, with additional confinement of the atoms by a light sheet.

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Breathing oscillations of a trapped impurity in a Bose gas

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Motivated by a recent experiment (Catani J. *et al.*, *Phys. Rev. A*, 85 (2012) 023623) we study breathing oscillations in the width of a harmonically trapped impurity interacting with a separately trapped Bose gas. We provide an intuitive physical picture of such dynamics at zero temperature, using a time-dependent variational approach. The amplitudes of breathing oscillations are suppressed by self-trapping, due to interactions with the Bose gas. Further, exciting phonons in the Bose gas leads to damped oscillations and non-Markovian dynamics of the width of the impurity, the degree of which can be engineered through controllable parameters. Our results, supported by simulations, reproduce the main features of the dynamics observed by Catani *et al.* despite the temperature of that experiment. Moreover, we predict novel effects at lower temperatures due to self-trapping and the inhomogeneity of the trapped Bose gas.

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Healing-length scale control of a Bose-Einstein condensate’s wavefunction

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Arbitrary engineering of a Bose-Einstein condensate’s (BEC’s) quantum state at the healing-length scale has many applications across ultracold atomic science, including atom interferometry [1], quantum simulation and emulation [2,3] and topological quantum computing [4]. However, to date the BEC wavefunction is most commonly manipulated with laser light, which is diffraction limited. Here we present a scheme, based upon radiofrequency (RF) resonance and magnetic field gradients, that can be used to apply arbitrary spatially-dependent phase shifts to the BEC order parameter at the healing-length scale.

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A spin Hall effect in ultracold atoms

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The spin Hall effect is a phenomenom that couples spin current to particle current via spin-orbit coupling. The effect may be used to develop useful devices for spintronics, which may have advantages over corresponding conventional electronic devices. In addition, the spin-Hall effect is intimately related to certain types of topological insulators. Spin-orbit coupling in an ultracold bosonic sample of ^{87}Rb has been demonstrated [1]. We now use this spin-orbit coupling to produce a spin Hall effect in a bosonic sample, the first demonstration of the effect in an ultracold atom system.

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The roles of the two zero and adjoint modes in the dynamics of dark soliton

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The dark solitons have been observed in BEC experiments. They are stable in 1D, but collapse in higher dimensions [1]. The existence of the zero and adjoint modes is known in the Bogoliubov-de Gennes (BdG) analysis, widely used to study the fluctuation and excitation spectrum in BECs. The zero mode corresponds to the Nambu-Goldstone mode, and the adjoint mode ensures thecompleteness of the set of eigenfunctions. In the case of the single-component system for which a translational symmetry is broken explicitly, there is only one zero mode. The roles of this zero and its adjoint modes are to translate the phase of condensate and to conserve the number of condensate, respectively evortex. We consider the case where the soliton exists in BEC and therefore a translational symmetry is spontaneously broken. Then the BdG equation has two pairs of the zero and adjoint modes, associated with the phase and translational symmetries. We discuss their roles in the dynamics of dark soliton.

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Mode competition in superradiant scattering of matter waves

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The coherent nature of Bose-Einstein condensates has led to new and rapid developments in atom optics and studies on coherent interaction between light and matter waves. Superradiant Rayleigh scattering in a Bose gas released from an optical lattice is analyzed with incident light pumping at the Bragg angle for resonant light diffraction. We show that competition between superradiance scattering into the Bragg mode and into end-fire modes clearly leads to suppression of the latter at even relatively low lattice depths. A quantum light-matter interaction model is proposed for qualitatively explaining this result [1]. Based on this mechanism of amplification of matter waves, we show a method to measure the global coherence function in a Bose gas loaded in a 1D optical lattice with a resolution of one lattice spacing [2].

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Bose gases Mo-074

Nucleation of vortices in a Bose Einstein Condensate

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We present experimental studies of the nucleation of small numbers of vortices in a Bose-Einstein Condensate. The vortices are nucleated in a rotating frame during evaporative cooling of the system, and using extraction imaging techniques [1], we produce images of a condensate being formed with vortices. We find that the condensate is created with a set number of vortices determined by the rotation frequency when passing through the BEC transition. After the condensate begins to form, we observe that additional vortices cannot be added to the system unless the rotation drives a collective mode of the condensate. We also observe that when multiple vortices are formed, they do not, in general, apppear in ordered configurations.

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Non-equilibrium dynamics of an unstable quantum many-body pendulum

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We measure the non-equilibrium quantum dynamics of a spin-1 Bose condensate, which exhibits Josephson dynamics in the spin populations that correspond in the mean-field limit to motion of a non-rigid mechanical pendulum. The condensate is initialized to a minimum uncertainty spin state corresponding to a unstable (hyperbolic) fixed point of the phase space, and quantum fluctuations lead to non-linear spin evolution along a separatrix. At early times, we measure squeezing in spin-nematic variables up to –8 dB [1]. At intermediate times, we measure spin oscillations characterized by non-Gaussian probability distributions that are in good agreement with exact quantum calculations up to 0.25 s. At longer times, atomic loss due to the finite lifetime of the condensate leads to larger spin oscillation amplitudes compared to no loss case as orbits depart from the separatrix [2]. This experiment demonstrates how decoherence of a many-body system can result in more apparent coherent behavior.

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Non-adiabatic preparation of spin crystals with ultracold polar molecules

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We study the growth dynamics of ordered structures of strongly interacting polar molecules in optical lattices. Using dipole blockade of microwave excitations, we map the system onto an interacting spin-1/2 model possessing ground states with crystalline order, and describe a way to prepare these states by non-adiabatically driving the transitions between molecular rotational levels. The proposed technique bypasses the need to cross a phase transition and allows for the creation of ordered domains of considerably larger size compared to approaches relying on adiabatic preparation.

We discuss the possibilities to use the dipole blockade of microwave excitations to create dissipation-induced bound states of polar molecules, and to cool an ultracold gas directly into a strongly-interacting many-body phase.

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Thermodynamics of Spin 3 ultra-cold atoms with free magnetization

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We study thermodynamic properties of a gas of spin 3 ^{52}Cr atoms across Bose Einstein condensation. Magnetization is free, due to dipole-dipole interactions. We show that the critical temperature for condensation is lowered at extremely low magnetic fields, when the spin degree of freedom is thermally activated [1]. The depolarized gas condenses in only one spin component, unless the magnetic field is set below a critical value Bc, below which a non-ferromagnetic phase is favoured due to spin dependent contact interactions [2]. We measure the magnetization of the gas versus the temperature; our results are compatible with predictions made respectively for a non-interacting gas with free magnetization above Bc, and for a non-interacting gas with fixed magnetization below Bc. In that case we obtain a hint for a double phase transition as predicted in [3]. In addition we demonstrate above Bc a spin thermometry efficient even below the degeneracy temperature.

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Bose-Einstein condensation of erbium

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We report on the achievement of the first Bose-Einstein condensation (BEC) of erbium atoms. This unconventional atomic species belonging to the lanthanide series possesses a large magnetic moment of seven Bohr magneton, making this species an ideal system for studying novel quantum phenomena arising from strong dipole-dipole interaction. Atoms captured in a magneto-optical trap operating on the intercombination line are directly loaded into an optical dipole trap (ODT). Evaporative cooling in an ODT shows a remarkable efficiency, allowing us to achieve a pure condensate containing 7×10^4 atoms. In addition, a Feshbach resonance found at a very low magnetic field of around 1 G allows us to tune the contact interaction precisely. When the contact interaction is tuned close to zero, we observe a *d*-wave collapse of the Bose-Einstein condensate, which provides a striking signature of strongly dipolar quantum gases, as previously shown in the Stuttgart experiment for chromium.

Quantum phases and anomalous hysteresis of dipolar Bose gases in a triangular optical lattice

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In recent years, increasing interest is devoted to the physics of ultracold gases with dipole-dipole interactions. We study the quantum phases and the hysteresis behavior of a dipolar Bose gas loaded into a triangular optical lattice [1]. Applying a large-size cluster mean-field method to the corresponding extended Bose-Hubbard model, we find that the interplay between the long-range interaction (proportional to $1/r^3$) and the frustrated geometry provides a rich variety of quantum phases, including some different solid and supersolid phases. We find that the transitions from supersolids to uniform superfluid are of first-order unlike the square-lattice case. It is also found that the system exhibits an anomalous hysteresis behavior, in which the transition can occur only unidirectionally [2], in the re-entrant first-order transition between superfluid and solid (or supersolid) phases.

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Properties of ultracold ground state LiCs molecules

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Ultracold LiCs molecules in the absolute ground state $X^1\Sigma^+$, $v''=0$, $J''=0$ were formed in a MOT by a single photo-association step [1]. The dipole moment of ground state levels has been determined and was found to be in excellent agreement with theoretical predictions [2,3]. We present also the creation of LiCs molecules directly in an optical dipole trap. Rate coefficients for inelastic collisions between deeply bound LiCs molecules [4] and cesium atoms are measured and the results are compared with predictions from the universal model of Idziaszek and Julienne [5]. We will also show experimental evidence for the occurrence of redistribution processes of internal states in a trapped sample of ultracold LiCs molecules driven by black-body radiation and spontaneous decay [6].

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Formation of ultracold fermionic NaLi Feshbach molecules

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We describe the formation of fermionic NaLi Feshbach molecules from an ultracold mixture of bosonic ^{23}Na and fermionic ^{6}Li [1]. Precise magnetic field sweeps across a narrow Feshbach resonance at 745 G result in a molecule conversion fraction of 5% for our experimental densities and temperatures, corresponding to a molecule number of 5×10^4. The observed molecular decay lifetime is 1.3 ms after removing free Li and Na atoms from the trap.

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Soliton lattices in dipolar Bose-Einstein condensates

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With the long-ranged dipole-dipole interaction, in this work, we investigate the formation of periodic soliton solutions, named as the soliton lattices, in both quasi-one- and two-dimensional dipolar Bose-Einstein condensates [1,2]. Due to the balance between the mean-field and dipole-dipole interaction, a crystallization of bright solitons can be formed in the lattice structure, which reveals a lower system Hamiltonian energy than that of isolated solitons. Moreover, the parameters space to support the therefore formed crystallized structure is characterized for the possible experimental realizations.

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Spin-injection spectroscopy of a spin-orbit coupled Fermi gas

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The coupling of the spin of electrons to their motional state lies at the heart of recently discovered topological phases of matter. We create and detect spin-orbit coupling in an atomic Fermi gas, a highly controllable form of quantum degenerate matter. We reveal the spin-orbit gap via spin-injection spectroscopy, which characterizes the energy-momentum dispersion and spin composition of the quantum states. For energies within the spin-orbit gap, the system acts as a spin diode. To fully inhibit transport, we open an additional spin gap, thereby creating a spin-orbit coupled lattice whose spinful band structure we probe. In the presence of s-wave interactions, such systems should display induced p-wave pairing, topological superfluidity, and Majorana edge states.

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Towards local probing of ultracold Fermi gases

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Ultracold fermionic gases are an ideal model system for the study of quantum many-body phenomena. Of particular interest are two-dimensional strongly correlated systems which can exhibit superfluidity and Berezinskii-Kosterlitz-Thouless-type transitions.

Here we present our new experimental setup aimed at studying two-dimensional strongly interacting Fermi gases. Lithium atoms are cooled all-optically using an in vacuo bow-tie resonator for high transfer and cooling efficiency. The quantum degenerate gas will then be placed between two high resolution microscope objectives for local readout and control. The present status of the experiment will be shown.

Mesoscopic transport of ultracold fermions through an engineered channel

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Experiments with ultracold fermions flowing through a narrow channel between two macroscopic reservoirs [1] have recently extended the concept of quantum simulation to mesoscopic physics. We report on a theoretical study [2] of such a setup, where the channel and the reservoirs consist of optical lattices. We describe the full equilibration process between the reservoirs — for finite temperatures and arbitrarily strong channel-reservoir couplings — using the Landauer formalism and non-equilibrium Green's functions. Our detailed analysis reveals significant quantum and thermal fluctuations of the atomic current despite intrinsic damping mechanisms. Moreover, we show how to control the current by either engineering specific optical lattice potentials or tuning the interactions between the fermions. As a result of the high control and slow dynamics of the equilibration process these new systems provide a versatile testbed for studying quantum transport.

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Two-component Fermi gas of unequal masses at unitarity: a quantum Monte Carlo approach

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We have studied the zero-temperature stability of a two-component Fermi gas at unitarity ($1 / k_F a = 0$) when the mass of the two components is different. To this end, we have carried out extensive calculations of the microscopic properties of the gas as a function of the mass ratio of heavy M to light m components using the fixed-node diffusion Monte Carlo method. This method has been used previously to characterize the unitary limit predicting results in close agreement with experiment [1]. Now, we extend our study to the case of different masses. Our many-body results show that the Fermi gas in this particular limit becomes unstable with respect to the formation of clusters when $M / m \geq 13(1)$. This instability is observed in a normal phase and is absent in simulations of a superfluid state. This interesting result is elucidated by analyzing the shape of the nodal surface of the three-body problem.

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An impurity in a Fermi sea on a narrow Feshbach resonance: a variational study of the polaronic and dimeronic branches

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We study the problem of a single impurity of mass M immersed in a Fermi sea of particles of mass m [1]. The impurity and the fermions interact through a s-wave narrow Feshbach resonance, so that the Feshbach length R_* naturally appears in the system. We use simple variational ansatz, limited to at most one pair of particle-hole excitations of the Fermi sea and we determine for the polaronic and dimeronic branches the phase diagram between absolute ground state, local minimum, thermodynamically unstable regions (with negative effective mass), and regions of complex energies (with negative imaginary part). We also determine the closed channel population which is experimentally accessible. Finally we identify a non-trivial weakly attractive limit where analytical results can be obtained, in particular for the crossing point between the polaronic and dimeronic energy branches.

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Fermionic Q-functions

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The Q-function for bosons allows all possible observables to be obtained from a unique positive probability distribution. This means that bosonic coherence and correlations can be readily obtained in a probabilistic way. We show that a Q-function is also possible for fermions, which can generate all moments and correlations in one distribution. This requires an approach that is more general than the Gilmore-Perelemov fermion coherent state. We obtain a Q-function by tracing SU(N) Gaussian operators combined with a Haar measure and a fermion density operator. Unlike previous definitions, this leads to a unique, positive phase-space representation for all possible fermionic states. This complements previous results on a fermionic P-function [1], which has been successfully used to calculate the ground-state of the Hubbard model [2]. We investigate approaches to calculating and measuring the fermionic Q-function, including computational methods and tomographic experiments.

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Topological phase transition and Majorana fermions in spin-orbit coupled Fermi gases

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We theoretically investigate the topological aspects of spin-orbit coupled Fermi gases under a Zeeman magnetic field. The most remarkable fact is that a chiral Majorana fermion emerges in the interface between topological and non-topological domains, suchas the edge and the singular vortex core [1]. Based on the Bogoliubov-de Gennes theory extended to the strong coupling regime, we first discuss the stability of the Majorana fermion bound at the edge of the array of a one-dimensional Fermi gas coupled with a non-Abelian gauge field, analogous to a junction system composed of quantum wire and *S*-wave superconductor. We also clarify the structure of chiral Majorana fermions inside the vortex core in the vicinity of the topological phase transition. The distinction from the results obtained in a spin-polarized Fermi gas with a *p*-wave Feshbach resonance [2] is discussed.

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Revealing the superfluid lambda transition in the universal thermodynamics of a unitary Fermi gas

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We have observed the superfluid phase transition in a strongly interacting Fermi gas via high-precision measurements of the local compressibility, density and pressure down to near-zero entropy. We perform the measurements by in-situ imaging of ultracold ^{6}Li at a Feshbach resonance. Our data completely determine the universal thermodynamics of strongly interacting fermions without any fit or external thermometer. The onset of superfluidity is observed in the compressibility, the chemical potential, theentropy, and the heat capacity. In particular, the heat capacity displays a characteristic lambda-like feature at the critical temperature of $T_c / T_F = 0.167(13)$. This is the first direct thermodynamic signature of the superfluid transition in a spin-balanced atomic Fermi gas. We measure the ground-state energy of the superfluid to be $3 / 5\xi N E_F$, with $\xi = 0.376(4)$. The experimental results are compared to recent Monte-Carlo calculations. Our measurements provide a benchmark for many-body theories on strongly interacting fermions, relevant for problems ranging from high-temperature superconductivity to the equation of state of neutron stars.

Spin-depairing transition in one-dimensional two-component Fermi gases

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We investigate one-dimensional two-component Fermi gases with a time-dependent gauge field on the spin sector. It is known that the ground state of two-component attractive Fermi gases is filled with bound states of up-spin and down-spin particles and the spin excitation has a gap, which is attributed to the appearance of fermionic superfluidity. By combining the methods of the Bethe ansatz with complex twists and Landau-Dykhne, we show that a spin-depairing transition occurs, which may represent a nonequilibrium transition from fermionic superfluids to normal states with spin currents. We analyze cases of Fermi-Hubbard and Yang-Gaudin models, and show how filling (density) affects the transition probability.

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Higher order longitudinal collective oscillations in a strongly interacting Fermi gas

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Measuring the collective oscillation frequencies of a trapped atomic gas is a useful tool to probe its thermodynamic properties. Previously, this technique was performed only with the lowest order collective modes, namely the surface modes (e.g. sloshing and quadrupole modes), and the breathing modes. Higher longitudinal modes with richer nodal structures *inside* the cloud have not been investigated mainly because of the difficulty to excite such modes. Here, we present our study on the higher longitudinal collective modes in an elongated cloud of a Fermi gas with unitarity-limited interactions. Unlike the lowest order modes which are temperature independent, these modes can be used to probe the Equation of State (EoS) of the gas at higher temperatures. We performed precise measurement of the oscillation frequencies, and observed a good agreement between our measurements and the predictions using the EoS measured by the MIT group [1].

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Towards strongly repulsive fermionic potassium

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A degenerate gas of fermionic atoms at its Feshbach resonance provides a clean and versatile system to study topics such as ferromagnetism, resonant superfluids, and few-body bound states. Our experiment consists of a crossed dipole trap below a microfabricated chip. The chip provides a tight magnetic trap for the initial stage of evaporative cooling. After transfer to the optical trap, it serves as a source of strong magnetic gradients, RF fields, and microwaves to manipulate the atoms. We will discuss several improvements to our apparatus, and report on our progress towards strongly interacting gases.

Anomalous concentration of atoms in standing light wave

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Steady-state momentum and coordinate distributions of two-level atoms under a standing light wave are explored. Theoretical results are calculated by applying the new method for finding a solution of quantum kinetic equation [1]. The method allows one to take into account recoil effects entirely for the light field of arbitrary intensity. In the case of weak field we gain a well-known result: the atoms are located in vicinity of the standing wave's antinodes, i.e. in minima of the quasiclassical optical potential (the laser field detuning is meant to be red). However, in the case of strong field a new effect is revealed: high concentration of atoms occurs at the nodes, i.e. at the maxima of the optical lattice potential. The qualitative interpretation of the results is given. The result provides throwing light on some features of atomic kinetics under strong light waves and may be found useful in atomic optics and nanolithography.

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Klein-tunneling of a quasirelativistic Bose-Einstein Condensate in an optical lattice

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A proof-of-principle experiment simulating effects predicted by relativistic wave equations with ultracold atoms in a bichromatic optical lattice that allows for a tailoring of the dispersion relation is reported [1]. In this lattice, for specific choices of the relativistic phases and amplitudes of the lattice harmonics the dispersion relation in the region between the first and the second excited band becomes linear, as known for ultrarelativistic particles. One can show that the dynamicscan be described by an effective one-dimensional Dirac equation [2].

We experimentally observe the analog of Klein-Tunneling, the penetration of relativistic particles through a potential barrier without the exponential damping that is characteristic for nonrelativistic quantum tunneling [3]. Both linear (relativistic) and quadratic (nonrelativistic) dispersion relations are investigated, and significant barrier transmission is only observed for the relativistic case.

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Negative absolute temperature for motional degrees of freedom

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Absolute temperature is one of the central concepts in statistical mechanics and is usually described as being strictly non-negative. However, in systems with an upper energy bound, also negative temperature states can be realized. In these states, the occupation probability of each basis state increases with energy. So far, they have been demonstrated only for localized degrees of freedom such as the spin of nuclei or atoms [1,2]. By using a Feshbach resonance in bosonic ^{39}K, we implemented the attractive Bose-Hubbard model in a three-dimensional optical lattice. Following a recent proposal [3,4], we were able to create a negative temperature state for motional degrees of freedom, strikingly resulting in a condensate at the upper band edge of the lowest band. This attractively interacting bosonic superfluid is thermodynamically stable, i.e. stable against mean-field collapse for abitrary atom numbers. We additionally investigated the characteristic timescale for the emergence of coherence in the ensemble, and found an intriguing symmetry between the negative temperature and positive temperature state.

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Tunable gauge potential for spinless particles in driven lattices

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We present a universal method to create a tunable, artificial vector gauge potential for neutral particles trapped in an optical lattice. A suitable periodic shaking of the lattice allows to engineer a Peierls phase for the hopping parameters. This schemethus allows one to address the atomic internal degrees of freedom independently. We experimentally demonstrate the realization of such artificial potentials in a 1D lattice, which generate ground state superfuids at arbitrary non-zero quasi-momentum [1].

This scheme offers fascinating possibilities to emulate synthetic magnetic fields in 2D lattices. In a triangular lattice, continuously tunable staggered fluxes are realized. Spontaneous symmetry-breaking has recently been observed for a π-flux [2]. With the presented scheme, we are now able to study the influence of a small symmetry-breaking perturbation.

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Robust critical states appear in ultra-cold atom gases

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We theoretically study the stationary states for the nonlinear Schrödinger equation on the Fibonacci lattice which is expected to be realized by Bose-Einstein condensates loaded into an optical lattice. Such a quasiperiodic system is realizable by using recently developed method for creating potentials through a holographic mask [1]. When the model does not have a nonlinear term, the wavefunctions and the spectrum are known to show fractal structures [2]. Such wavefunctions are called critical.

In our study, we numerically solve the nonlinear Schrödinger equation on the one-dimensional Fibonacci lattice and propose some mathematical theorems to present a phase diagram of the energy spectrum for varying the nonlinearity. The phase diagram consists of three portions, a forbidden region, the spectrum of critical states, and the spectrum of stationary solitons. Critical states are considered fragile in perturbations in general. However, we show that the energy spectrum of critical states remains intact irrespective of the nonlinearity in the sea of a large number of stationary solitons. We expect the first direct detection of the critical state in the ultra-cold atom gases.

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Strong suppression of transport due to quantum phase slips in 1D Bose gases

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Recent experiments [1, 2, 3] have intensively investigated the transport of 1D Bose gases in optical lattices and shown that the transport in 1D is drastically suppressed even in the superfluid state compared to that in higher dimensions. Motivated by the experiments, we study the superflow decay of 1D Bose gases via quantum nucleation of phase slips by means of both analytical instanton techniques and numerically exact time-evolving block decimation method. We find that the nucleation rate Γ of a quantum phase slip in an optical lattice exhibits a power-law behavior with respect to the flow momentum p as $\Gamma / L \propto p^{2K-2}$ when $p << \hbar / d$, where L, K, and d denote the system size, the Luttinger parameter, and the lattice spacing [4]. To make a connection with the experiments, we relate the nucleation rate with the damping rate of dipole oscillations in a trapped system, which is a typical experimental observable [1, 2], and show that the suppression of the transport in 1D is due to quantum phase slips. We also suggest a way to identify the superfluid-insulator transition point from the dipole oscillations.

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Generation of tunable correlated atom beams in an optical lattice

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Spontaneous four wave mixing (SFWM) of matter waves is a source of non-classical atomic pair states, similar to the twin photon states generated through parametric down-conversion and widely used in quantum optics: Momentum correlations [1] and sub-shot noise relative number fluctuations [2] were demonstrated for atoms produced through SFWM in free space. Using a scheme similar to [3], we perform here SFWM in a moving 1D optical lattice, from a metastable helium quasi-BEC. Thus, pairs of atoms are efficiently scattered into two matter beams, whose momenta are precisely tunable. The ability to control the beam population makes this source suitable for a variety of quantum atom optics experiments, in the limit of either highor low mode population. We study the beams' correlation properties, which are crucial for such applications.

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Dynamic structure factor of Bose-Bose mixtures in an optical lattice

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Binary mixtures of Bose gases confined in an optical lattice have been realized in experiments [1]. Previous theoretical studies have predicted various quantum phases, including superfluid (SF), Mott insulator (MI), paired SF (PSF), and counterflow SF (CFSF) [2, 3]. We study elementary excitations of Bose-Bose mixtures in an optical lattice by analyzing the Bose-Hubbard model within the time-dependent Gutzwiller approximation. Applying a linear response theory, we calculate the density response functions of Bose-Bose mixtures in SF, PSF, and CFSF phases and show that characteristics of these phases are clearly manifested in the dynamical properties. We find that one-component density fluctuation induces the in-phase mode for the attractive interspecies interaction and the out-of-phase mode for the repulsive interspecies interaction.

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Optical flux lattices for ultra cold atoms using Raman transitions

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We theoretically investigate the optical flux lattices [1,2] produced for ultra-cold atoms subject to laser fields where both the atom-light coupling and the effective detuning are spatially periodic. We explore the geometric vector potential and the magnetic flux it generates, as well as the accompanying geometric scalar potential. We show how to understand the gauge-dependent Aharonov-Bohm singularities in the vector potential, and calculate the continuous magnetic flux through the elementary cell in terms of these singularities. The analysis is illustrated with a square optical flux lattice. We conclude with an explicit laser configuration yielding such a lattice using a set of five properly chosen beams with two pairs counter propagating along $\mathbf{e}_x$, and $\mathbf{e}_y$ along with a single beam along $\mathbf{e}_z$. We show that this lattice is not phase-stable, and identify the one phase-difference that affects the magnetic flux. Thus armed with realistic laser setup, we directly compute the Chern number of the lowest Bloch band to identify the region where the non-zero magnetic flux produces a topologically non-trivial band structure.

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Non-equilibrium dynamics, heating, and thermalization of atoms in optical lattices

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A key challenge in current experiments with ultracold atoms is to produce low entropy many-body states in optical lattices. In this context, it is very important to characterize and control heating processes, which arise from various sources including spontaneous emissions and classical fluctuations of the lattice potential. These processes are intrinsically interesting, as there often a separation of timescales between some excitations that thermalize rapidly, and some that do not properly thermalize in the duration of an experimental run, so that the non-equilibrium many-body dynamics of thermalization play a crucial role. Here we first consider how different many-body states of bosons and fermions are sensitive to amplitude fluctuations of the lattice potential, and we show how a dressed lattice scheme could provide control over such noise for atoms in the lowest Bloch band of a lattice. We then present results on the thermalization of bosons in an optical lattice in the presence of spontaneous emissions.

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Reservoir-assisted band decay of ultracold atoms in a spin-dependent optical lattice

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We report measurements of reservoir-assisted decay of atoms in excited bands in a cubic, spin-dependent optical lattice. We adiabatically load a 87Rb BEC in a mixture of mF = 0 and mF = − 1 states into a 3D lattice. Atoms in the mF = − 1 state experience a strong lattice potential. On the contrary, atoms in the mF = 0 state form a harmonically trapped superfluid reservoir since they do not interact with the lattice. We transfer atoms in the mF = − 1 state to the first excited band using stimulated Raman transitions, and we measure the decay rate to the ground band induced by collisions with the reservoir.

One-way quantum computation with ultra-narrow optical transition of ^{171}Yb atoms

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Multi-particle cluster state was successfully created for rubidium atoms, by using an electronic spin dependent potential[1]. Creation of the cluster state for nuclear spin is desirable because of its long coherence time. Here we present a method to create a cluster state for nuclear spins of ^{171}Yb atoms by using ultra-narrow optical transition ($^1S_0 \leftrightarrow {}^3P_2$, λ = 507nm). While this transition has an extremely narrow line-width of 10mHz, our calculation says a potential depth of 10μK can be created using laser power of 100mW, where the detuning and the beam waist are set to 150kHz and 30μm, respectively. Since the $^3P_2$ excited state has a large hyperfine splitting(6.7GHz), the potential is dependent on the nuclear spin state. We experimentally generated 507nm of the second harmonic light using a PPKTP crystal, where a fundamental light (1014nm) was prepared by using a laser diode and a tapered amplifier. Obtained power of the second harmonic light was 150mW which is enough to implement our plan.

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High-resolution optical spectra of bosonic ytterbium atoms in an optical lattice: Comparison between numerical calculations and experiments

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We investigate laser spectra of bosonic ^{174}Yb atoms in a three dimensional optical lattice both theoretically and experimentally. With the aid of a ultra-narrow optical transition of the Yb atoms [1], high-resolution spectra are systematically measured by varying the lattice depth. We also perform the following numerical simulations; first, determine parameters of the bosonic Hubbard model with the *ab initio* manner; then, analyze this model based on the Gutzwiller approximation considering finite temperature effects; finally, calculate the excitation spectra described by the Lehman representation. Here we consider modifications of the model parameters due to the formation of two-body bound states induced by confinement of the lattice potential [2]. The numerical simulations clarify how the spectra change depending on both temperatures and lattice depths. By comparing the numerical results with the measured spectra, we discuss phase transitions of the present system at finite temperatures.

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Analysis for diffusion of fermion in optical lattice by lattice oscillation

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Many intriguing phenomena such as Mott insulator and antiferromagnetism have been observed in the cold fermion gas systems in the optical lattice. They are well described by the Hubbard model, whose numerical analyses are performed in various ways, e.g. Gutzwiller anzatz, density matrix renormalization, and quantum Monte Carlo methods and so on. Recent advance in experimental technique made it feasible to perform more complicated experiment. Fermion dynamics is slower than boson one due to the Pauli blocking, so the observation of Mott insulator transition for cold fermion systems is rather difficult. We analyze the Hubbard model in the optical lattice and perform numerical simulation with Gutzwiller anzatz. We calculate various observable quantities and compare them to experiments [1, 2]. In addition, we discuss the time scale of the diffusion and propose a possible method in which the observation of Mott insulator transition in experiments is easier.

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A diffusion Monte Carlo approach to boson hard-rods in 1D optical lattices

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We present a zero-temperature quantum Monte Carlo calculation of a system of hard-rods trapped in a purely 1D optical lattice by means of a diffusion Monte Carlo calculation. This method provides a continuous treatment of the positions contrarily to the widely extended Bose-Hubbard (BH) models allowing for a direct comparison both with BH models and experimental results [1]. We shall analyze the phase-structure of the model and characterize the different phases by analising some of its correlation functions. We present an estimate of a superfluid density based on an extension of the winding number technique to zero temperature [2], although its meaning in a purely 1D system is yet unclear. The off-diagonal one body density matrix shall be used to argue the nature of this non-isolating phase.

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Phase diagram of 1D fermionic optical lattices with spatially alternating interaction

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Spatial control of on-site interaction within ultracold atomic optical lattices is realized in recent experiment [1]. We focus on simple systems with spatially alternating on-site intaractions. We present a phase diagram of 1D fermionic optical lattices with spatially alternating on-site interaction by using density matrix renormalization group (DMRG) method. Our model is described by simple Hubbard model with spatially alternating on-site interaction U_1 and U_2. Employing DMRG method, we calculate that local density profile, spin-spin correlation function, and binding-energy. Phase diagram shows gradually changing as a function of spatially alternating interaction i.e., we find metallic, ordered state, Mott insulator phases. We discuss various desiderata for properties of new phase, we calculate dynamical properties by using dynamical DMRG method [2]. We present multiple band structure due to the U_1/U_2. Furthermore, focus on phase boundary, we can find gapped state closed as linearly-approximated structure.

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Quantum information Mo-110

High-rate entanglement of two ions using single photon detection

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We will present our experimental observation of entanglement of two effectively meter distant atomic qubits using single photon interference [1]. A weak laser field is used to Raman scatter a single photon from two Barium ions that are Doppler cooled in the Lamb-Dicke regime. Ensuring that the two possible emission paths are indistinguishable at a single photon counter, we show that a single detection event projects the two-ion state into a maximally entangled Bell state [2]. We also demonstrate that we can control the phase of the entangled states by tuning the path length difference between the two photonic channels.

A two orders of magnitude increase in the entanglement generation rate was measured compared to remote entanglement schemes that use two-photon coincidence events. This result is important for efficient distribution of quantum information over long distances using trapped ion architectures.

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Heralded photonic interaction between distant single ions

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Two single Ca^+ ions interact over 1 m distance through emission and absorption of single resonant photons. Single-photon emission in the sender ion is continuous or triggered; absorption in the receiver is signaled by a quantum jump. For continuous emission of photons at 393 nm, the sender ion is driven by lasers such that the short-lived $P_{3/2}$ level is populated. Decay to the $S_{1/2}$ ground state generates photons at 393 nm, of which ~ 3% are transmitted to another ion trap. The receiver ion is continuously laser-cooled, emitting fluorescence at 397 nm. Sudden drops in the fluorescence mark the absorption of single 393 nm photons, transferring the ion to the long-lived $D_{5/2}$ state. We observe such quantum jumps at up to 1 s^{-1} rate. For pulsed photon generation, the sender ion is optically pumped to the $D_{5/2}$ state. Then a laser pulse at 854 nm excites it to the short-lived $P_{3/2}$ level, releasing a single photon at 393 nm. Frequency, polarization, and temporal shape of the 393 nm photon are controlled by the exciting pulses. Correlation analysis of the pulsed photon generation and the quantum jumps is currently underway.

Development of ion-trap technologies for quantum control of multi-species ion chains

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We are developing setups for quantum information processing, simulation, and state engineering with trapped atomic ions. We will trap beryllium and calcium ions simultaneously in segmented linear Paul traps. One system is optimised for quantum control and separation of ion strings. The second setup is a micro-scale surface-electrode trap operating at 4K. In-vacuum high-speed switches allow ultra-fast ion shuttling. For Be^+ we have developed a 7.2W source at 626nm, using sum-frequency generation; this is further frequency doubled with BBO crystals in resonant cavities. The lasers required for Ca^+ are commercial systems stabilised to custom optical cavities, with finesses up to 290 000. Fluorescence is detected from both ion species with high NA imaging systems, designed with in-vacuum objective lenses. A custom high-speed FPGA control system is under-development that will be used to generate phase-coherent pulses.

Coherent manipulation of optical properties in a hot atomic vapor of helium

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It is well known that ultranarrow electromagnetically induced transparency (EIT) resonances can be observed in a Λ-system of metastable helium at room temperature using the $2^3S_1 \rightarrow 2^3P_1$ transition [1]. We report the experimental observation of another type of ultranarrow resonance, even slightly narrower than the EIT one, in the same system. It is shown to be due to coherent population oscillations in two coupled open two-level systems [2]. We also explore the physics of the $2^3S_1 \rightarrow 2^3P_0$ transition in two different tripod configurations, with the probe field polarization perpendicular and parallel to the quantization axis, defined by an applied weak transverse magnetic field. In the first case, the two dark resonances interact incoherently and merge together into a single EIT peak with increasing coupling power. In the second case, we observe destructive interference between the two dark resonances inducinga narrow absorption resonance at the line center [3].

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Long-lived qubit from three spin-1/2 atoms

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A system of three spin-1/2 atoms allows the construction of a reference-frame-free (RFF) qubit in the subspace with total angular momentum $j = 1/2$. The RFF qubit stays coherent perfectly as long as the spins of the three atoms are affected homogeneously. The inhomogeneous evolution of the atoms causes decoherence, but this decoherence can be suppressed efficiently by applying a bias magnetic field of modest strength perpendicular to the plane of the atoms. The resulting lifetime of the RFF qubit can be many days, making RFF qubits of this kind promising candidates for quantum information storage units. Specifically, we examine the situation of three ^6Li atoms trapped in a CO_2-laser-generated optical lattice and find that, with conservatively estimated parameters, a stored qubit maintains a fidelity of 0.9999 for two hours.

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Adiabatic passage at Rydberg blockade for single-atom loading and quantum gates

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Mesoscopic ensembles of strongly interacting ultracold atoms trapped in optical lattices or in optical dipole trap arrays are promising candidates to implement a large-scale quantum register. Quantum information can be encoded in the collective states of atomic ensembles and processed by quantum logic gates exploiting Rydberg blockade of the laser excitation. If dipole traps or optical lattices are loaded from a cold atom cloud, the number of atoms in each site is random. Therefore, the frequency of Rabi oscillations between collective states of the atomic ensembles in the blockade regime is undefined, and single-atom excitation is not deterministic, as required for high-fidelity operations. We propose to use adiabatic passage to overcome the dependence of the Rabi frequency on the number of interacting atoms [1]. We show that both deterministic excitation of a single Rydberg atom and controlled-phase quantum gates can be implemented using chirped excitation or STIRAP in mesoscopic ensembles with unknown number of atoms. This allows for high-fidelity single-atom loading of optical lattices and quantum logic operations with randomly loaded ensembles.

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An elementary quantum network of single atoms in optical cavities

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Quantum networks are at the heart of quantum communication and distributed quantum computing. Single atoms trapped in optical resonators are ideally suited as universal quantum network nodes capable of sending, receiving, storing, and releasing photonic quantum information. The reversible exchange of quantum information between such single-atom cavity nodes is achieved by the coherent exchange of single photons. Here we present the first experimental realization of an elementary quantum network consisting of two atom-cavity nodes located in remote, independent laboratories [1]. We demonstrate the faithful transfer of arbitrary quantum states and the creation of entanglement between the two atoms. We characterize the fidelity and lifetime of the maximally entangled Bell states and manipulate the nonlocal state via unitary operations applied locally at one of the nodes. This cavity-based approach to quantum networking offers a clear perspective for scalability.

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Addressable parallel quantum memory for light in cavity configuration

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We propose a cavity-based scheme for parallel spatially multimode quantum memory for light. A memory cell analogous to the previously proposed quantum volume hologram of [1] is placed into spatially multimode single-port ring cavity. The cell is illuminated with off-resonant counter-propagating quantum signal wave and strong classical reference wave. The cavity configuration allows for storage and retrieval with lower optical depth, and due to a uniform distribution of the field and spin amplitudes, the collective spin is excited more effectively. We reveal optimal temporal modes of the input quantized signal allowing for efficient state transfer to the memory degrees of freedom, and evaluate memory capacity in terms of the transverse modes number. We also describe a method of "on-demand", or addressable retrieval from the memory of quantized spatial modes, which is important [2] for application of memory in quantum repeaters.

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Quantum logic operations in $^{40}Ca^+$ and ^{43}Ca trapped-ion qubits

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We have successfully implemented a magnetic-field-insensitive qubit in the intermediate magnetic field (146G) in the ground state manifold of $^{43}Ca^+$ using an in-house designed and microfabricated surface ion trap. The trap incorporates integrated microwave waveguide resonators to drive the qubit transitions at 3.2 GHz. We intend to implement motional gates using the large gradient present in the evanescent field above the microwave resonators as recently demonstrated [1]. Preliminary results indicate that the trap has a heating rate amongst the lowest measured in a surface trap at room temperature, and that the qubit has a coherence time of order 10 s.

Secondly, we are aiming to implement a two-qubit gate using two different isotopes of calcium ($^{40}Ca^+$ and $^{43}Ca^+$) in a macroscopic linear Paul trap. The isotope shift (~ 1 GHz) allows us to individually address the two ions. Transitions are driven by two Raman lasers which manipulate both isotopes with low scattering error and high Rabi frequency [2]. We have achieved Raman sideband cooling close to the ground state ($\bar{n} < 0.1$) and simultaneous readout on both isotopes.

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Quantumness of correlations and entanglement are different resources

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We investigate the resource power of general quantum correlations [1] (as measured by the geometric discord [2]) versus entanglement in a class of cat-like states ρ_{AB} of a two-level atom and a harmonic oscillator. The entanglement in these states can reach the maximum while the geometric discord is limited by the temperature T of the oscillator. We design two hybrid communication protocols that take advantage of either resource. One is a teleportation scheme where Bob teleports an unknown atomic state to Alice, via the shared resource ρ_{AB}: the fidelity reaches unity for any T. The second is a remote state preparation protocol where Alice can measure the atom to remotely prepare Bob's oscillator in some (known to Alice) state: here the fidelity is upper bounded by the geometric discord, decreasing with increasing T. We conclude that quantumness of correlations and entanglement are truly different resources, and different communication scenarios can exploit one ignoring the other, and vice versa.

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Nonlocality of a cat state following non-Markovian evolutions

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We study the time evolution of Bell-CHSH functions for a spin-oscillator cat-like state evolving according to two models for non-Markovian dynamics, and we find that the different facets of non- Markovianity affect nonlocality in different and non-obvious ways [1]. In the first model, Brownian motion is considered for the oscillator system and we find that it affects the non-local nature of a cat state in quite a significant way when the cut-off frequency of the Brownian bath is much smaller than the natural oscillation frequency of the oscillator, i.e. in the regime that would correspond to a strong non-Markovian limit. In this case, large-amplitude revival peaks are found, showing the kick-back mechanism that the memory-keeping environment can exert over the system. In the second model, we use a post-Markovian master equation for the spin part and we find that it is unable to induce a nonmonotonic decay of the Bell-CHSH function. Yet, such dynamics is nondivisible and as such it deviates from the prescriptions commonly accepted for Markovianity.

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Modeling single photon production in RASE

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Rephased Amplified Spontaneous Emission (RASE) from an ensemble of rare-earth ions has been observed in experiment [1], however detector inefficiencies and noise on the signal have prevented non-classical correlations from being demonstrated. This work presents theoretical modelling of both Amplified Spontaneous Emission (ASE) from the ensemble when all ions are in the excited state, and the RASE rephasing process, once an emission has been detected and the population of the ensemble has been inverted. The optimal optical depth of the ion ensemble is found to maximise the production of single-photon states while minimising multi-photon production, and also to maximise the probability of a rephased photon being emitted. This will be used to chose an operating point for future RASE experiments. The emission profile of an ensemble prepared after a multi-photon detection is also calculated.

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The dimension of nonsignaling box

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It is demonstrated that genuine random numbers can be generated from a system consisting of two entangled atoms (ions) [1]. This nonlocal system can be characterized as a bipartite binary input and binary output box [2]. Due to the irreducible randomness intrinsic to a quantum system, the relationship between inputs and outputs is characterized by a conditional joint probability distribution $P(ab \mid xy)$, which is determined by the quantum state and measurement setups. Notably, toavoid superluminal (fast-than-light) communication, a nonlocal box does not allow signaling. Our work shows that one can use correlation functions to produce all the probability distribution of a nonsignaling box. As a result, the number of independent parameters (the dimension) of a nonsignaling box is the number of its correlation functions.

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Quantum computing with incoherent resources and quantum jumps

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Spontaneous emission and the inelastic scattering of photons are two natural processes usually associated with decoherence and the reduction in the capacity to process quantum information. Here [1] we show that, when suitably detected, these photons are sufficient to build all the fundamental blocks needed to perform quantum computation in the emitting qubits while protecting them from deleterious dissipative effects. We exemplify this by showing how to efficiently prepare graph states for the implementation of measurement-based quantum computation.

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Reversal of a strong quantum measurement by quantum error correction

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The strong measurement of a quantum state is a non-reversible process that projects the system onto the eigenstates. Therefore, it is generally not possible to reconstruct the state prior to the measurement. However, the measurement projection can also beregarded as a qubit error which can be rectified by quantum error correction techniques. We report on the experimental realization of such quantum measurement reversal in a system of trapped Calcium ions. We adapt the 3-qubit quantum error correction code presented in [1] which corrects for single qubit phase flips errors and is therefore ideally suited for the reversal of measurement projection of one of the three qubits. Here, the quantum information is encoded in an entangled logical qubit $\alpha|+++\rangle+\beta|---\rangle$ of three physical qubits. The measurement projection of a single physical qubit onto $|0\rangle$ and $|1\rangle$ does not reveal any information on the state of the logical qubit, i. e. the quantum information is protected by entanglement. The error correction sequence finally rectifies phase errors that occurred during the measurement.

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Nonlinear optics with double slow light pulses

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We experimentally demonstrated a double slow light scheme (DSL) based on double electromagnetically induced transparency (EIT) in optically dense, cold cesium atoms [1]. The cross-Kerr nonlinearity between the two weak slow-light pulses is obtained through the asymmetric five-level M-type system formed by the two sets of EIT systems [2]. The group velocities of the two pulses are tuned to a matched condition to prolong the interaction time [3]. In the first DSL experiment to implement the cross-phase modulation, we have obtained a cross-phase shift of 10^{-6} radian per photon [1]. However, the nonlinear efficiency is still lower than that of four-level N-type system without DSL scheme [4] due to a linear loss in the switching EIT system in which a small two-photon detuning is introduced to obtain nonzero cross-Kerr nonlinearity. We have successfully demonstrated an improved DSL scheme in which a nonzero cross-Kerr exists even with both EIT systems on their two-photon resonance. We studied the nonlinear process of all optical switching and have overcome the N-type limit by a factor of 2.6. The nonlinear efficiency can be further improved by increasing the optical depth of the medium.

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Optical diamond nanocavities for integrated quantum networks

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Nitrogen-Vacancy (NV) centers in diamond have emerged as a promising solid-state platform for quantum communication, quantum information processing [1], and metrology. Engineering the light-matter interaction between NV centers and nanophotonic devices can greatly enhance the performance of these systems. We demonstrate fabrication of diamond-based optical cavities containing and coupled to individual NV centers, with the potential for dramatic enhancement of the NV center's zero-phonon line via the Purcell effect. Localized modes having quality factors up to 6,000 have been achieved, resulting in a Purcell factor of 10. In addition, we investigate the properties of NV centers inside nanoscale structures and present novel techniques to ensure desirable spectral properties. These devices could enable strong coupling between the cavity field and NV centers, in addition to intriguing applications such as single photon transistors and quantum networks.

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Coherent manipulation of a single hard x-ray photon

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Seeking for elegant ways of performing computations on the most compact scale is one of the crucial objectives in both fundamental physics and information technology. The photon as the flying qubit is anticipated to be the fastest information carrier and provide the most efficient computing. However, extending Moore's law to the future quantum photonic circuits must meet the bottleneck of the diffraction limit, e.g., few hundred nm for the optical region. The pioneering experiment [1] of incoherent photon storage were carried out with the wavelength of 0.86 Å and might overcome this size issue. Using this scheme, another novel idea [2] has also shown the potential of creating single-photon entanglement in the x-ray regime. Here we will demonstrate a new way of manipulating a single hard x-ray photon, including the coherent storage and the phase modulation of its wave packet [3]. We expect that such x-ray quantum optics schemes will help advancing quantum computation on very compact scales.

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Photon localization in cold atoms: from Dicke to Anderson

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The quest for Anderson localization of waves is at the center of many experimental and theoretical activities. Cold atoms have emerged as interesting quantum system to study coherent transport properties of light. Initial experiments have established that dilute samples with large optical thickness allow studying weak localization of light. The goal of our research is to study coherent transport of photons in dilute and dense atomic samples. One important aspect is the quest of Anderson localization of light with cold atoms and its relation to Dicke super- or subradiance.

We present experimental and theoretical results [1-3], emphasizing the role of long range interactions between the atomic dipoles resulting in dominant global Dicke like synchronization over Anderson localization in coherent wave transport in resonant media.

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Non-classical statistics of strongly-interacting dark-state Rydberg polaritons

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Interfacing light and matter at the quantum level is at the heart of modern atomic and optical physics and is a unifying theme of many diverse areas of research. A prototypical realization is electromagnetically induced transparency (EIT), whereby quantuminterference gives rise to long-lived hybrid states of atoms and photons called dark-state polaritons [1]. in a fully coherent and reversible way. Here we report the observation of strong interactions between dark-state polaritons in an ultracold atomic gas involving highly excited (Rydberg) states. By combining optical imaging with counting of individual Rydberg excitations we probe both aspects ofthis atom-light system. Extreme Rydberg-Rydberg interactions give rise to a polariton blockade, which is revealed by a strongly nonlinear optical response of the atomic gas. For our system the polaritons are almost entirely matter-like allowing us to directly measure the statistical distribution of polaritons in the gas. For increasing densities we observe a clear transition from Poissonian to sub-Poissonian statistics, indicating the emergence of spatial and temporal correlations between polaritons. These experiments, which can be thought of as Rydberg dressing of photons, show that it is possible to control the statistics of light fields, and could form the basis for new types of long-range interacting quantum fluids.

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Superradiant phase transition with ultracold atoms in optical cavity

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We discuss the dispersive coupling of a Bose-Einstein condensate to the field of a high-*Q* optical cavity. The optical field mediates an infinite-range atom-atom interaction which can induce the self-organization of a homogeneous BEC into a periodically patterned distribution above a critical driving strength [1]. This self-organization effect can be identified with the superradiant quantum phase transition of the Dicke model, however in our system, the role of the internal atomic states are played by the motional states of the condensate [2]. The cavity photon loss limits the observation of the quantum phase transition in the ground state and for long times one observes a non-equilibrium phase transition in the steady state of the system. We show that the critical fluctuations survive in the steady state, however the critical exponents are different from those in the ground state, furthermore the atom-field entanglement is peaked but not divergent in the steady state [3].

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Generating non-Gaussian states using collisions between Rydberg polaritons

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We investigate the deterministic generation of quantum states with negative Wigner functions which arise due to giant non-linearities originating from collisional interactions between Rydberg polaritons. The state resulting from the polariton interactions may be transferred with high fidelity into a photonic state, which can be analyzed using homodyne detection followed by quantum tomography. We obtain simple analytic expressions for the evolution of polaritonic states under the influence of Rydberg-Rydberg interactions. In addition to generating highly non-classical states of the light, this method can also provide a very sensitive probe of the physics of the collisions involving Rydberg states.

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Nonlinear optics with cold Rydberg gases

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Owing to the high sensitivity of Rydberg atoms to external fields and to interactions among themselves, ultracold Rydberg gases provide an ideal system for nonlinear optics. Here, we investigate interaction effects on the nonlinear process such as four-wave mixing (FWM) and Electromagnetically induced transparency (EIT). The combination of interacting Rydberg gases and this kind of quantum coherent process has recently attracted considerable theoretical and experimental interest, as it holds promise for realizing extremely large nonlinearities by exploiting the exaggerated interactions between Rydberg atoms. We present a classical many-body approach to investigate mechanisms behind optical nonlinearities arising from strong Rydberg-Rydberg interactions. Our method can describe large numbers of excited atoms, and, at the same time, properly account for strong correlations and many-body entanglement as well as dissipative processes.

Perspectives for laboratory implementation of the DLCZ protocol for quantum repeaters

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We analyze the efficiency and scalability of the DLCZ protocol for quantum repeaters through experimentally accessible measures of entanglement for the system, taking into account crucial imperfections of the stored entangled states. We calculate the degradation of the final state of the quantum-repeater linear chain for increasing sizes of the chain, and characterize it by a lower bound on its concurrence and the ability to violate the CHSH inequality. The minimum purity of the initial state, required to succeed in the protocol as the size of the chain increases, is obtained. We also provide a more accurate estimate for the average time required to succeed in each step of the protocol. The minimum purity analysis and the new time estimates are then combined to trace the perspectives for implementation of the DLCZ protocol in present-day laboratory setups.

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Feedback in a cavity QED system for control of quantum beats

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Conditional measurements on the undriven mode of a two-mode cavity QED system prepare a coherent superposition of ground states that generate quantum beats [1]. The continuous drive of the system, through the phase interruptions from Rayleigh scattering, induces decoherence that manifests itself in a decrease of the amplitude and an increase of the frequency of the oscillations [2]. Our recent experiments implement a feedback mechanism to protect the quantum beat oscillation. We continuously drive the system until we detect a photon that heralds the presence of a coherent superposition. We then turn the drive off to let the superposition evolve in the dark, protecting it against decoherence. We later turn the drive back on to measure the amplitude and frequency of the beats. The amplitude can increase by more than fifty percent while the frequency returns to the unshifted value. Worksupported by NSF, CONACYT, and the Marsden Fund of RSNZ.

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A superradiant laser with <1 intracavity photon

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We will describe a recently demonstrated cold-atom Raman laser that operates deep into the superradiant or bad-cavity regime [1]. The system operates with <1 intracavity photon and with an effective excited state decay linewidth <1 Hz. This model system demonstrates key physics for future active optical clocks (similar to masers) that may achieve frequency linewidths approaching 1 mHz due to 3 to 5 orders of magnitude reduced sensitivity to thermal mirror noise. The measured linewidth of our model system demonstrates that the superradiant laser's frequency linewidth may be below the single particle dephasing and natural linewidths, greatly relaxing experimental requirements on atomic coherence. The light field's phase provides a continuous non-destructive measurement of the collective atomic phase with a precision that in-principle can be near the standard quantum limit. The possibilities for future hybrid active/passive atomic clocks will be discussed.

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Dissipative preparation of entangled steady states in cavity QED and ion traps

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We propose various schemes for the dissipative preparation of a maximally entangled steady state of two atoms in an optical cavity. Harnessing the natural decay processes of spontaneous emission and cavity photon loss, we apply an effective operator formalism [1] to identify and engineer effective decay processes, which reach an entangled steady state of two atoms as the unique fixed point of the dissipative time evolution. For trapped ions we achieve the same result by using engineered spontaneous emission. We investigate various aspects which are crucial for the experimental implementation of our schemes in existing cavity QED and ion trap setups. Our study shows promising performance for present-day and future experimental systems, in particular a qualitative improvement in the scaling of the fidelity error as compared to unitary protocols for cavity QED [2].

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Propagation of a light pulse in the EIT medium modified by the microwave field

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A coherent preparation of an atomic medium by a laser light can lead to modifications of its optical properties characterized by the electric susceptibility. It is thus possible to influence a propagation of a light pulse in such a medium. The most important effect in this class is the Electromagnetically Induced Transparency (EIT) [1]. Recently a number of papers have been devoted to a realization and control of EIT in the closed loop configuration, especially in a Λ-type system with an additional microwave field coupling two lower states [2, 3]. The main topic of my work is to investigate the propagation of a probe pulse of a given shape and finite duration inside an atomic sample under EIT with the additional microwave field.

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Towards a loophole-free Bell test with atom-photon entanglement

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Since the original Bell's idea a lot of different Bell tests have been performed, mostly using the means of quantum optics. Apart from their fundamental significance, the Bell tests are a very useful tool in the quantum information processing tasks, namely in the device independent scenarios. Necessary requirement to assess the validity of a Bell test is to close both the detection and locality loopholes, the goal with still missing experimental evidence. It was shown in [1, 2, 3], that a hybrid entangled state of a single atom and the coherent light field can violate the Bell inequality with moderate transmission and detection efficiencies. Here we present an experimental proposal realizing such a hybrid entangled states by means of cavity QED with a single atom. We show, that this state can be achieved using realistic experimental parameters available up-to-date yielding the CHSH violation of up to 2.25 and propagation distances of order of 100 meters for optical systems.

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Salecker-Wigner-Peres clock and tunneling times for localized particles

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We address the longstanding problem of defining the time for a particle to tunnel through a potential using the Salecker-Wigner-Peres (SWP) quantum clock [1]. After a brief discussion the applicability of such clock to general potentials [2] and the role of the localizability of the tunneling particle [3], we argue for the need to perform a post-selection of the final state to obtain an average that can be interpreted as transmission (or reflection) time and obtain an expressionfor an average tunneling time valid for general localized potentials. The properties of this time scale are investigated both in the non-relativistic and relativistic scenarios – numerical results are presented for several potentials and, in particular,it is shown that this time scale does not exhibit the Hartman effect (nor its generalized version). Finally, the interpretation of the SWP clock and of the results obtained are discussed in the context of the weak measurement theory.

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Towards quantum Zeno dynamics with Rydberg atoms in a cavity

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Quantum Zeno dynamics (QZD) generalizes the quantum Zeno effect in which repeated measurements inhibit the coherent evolution of a system [1]. In QZD, the measured observable has degenerate eigenspaces in which the system evolution is confined. We have proposed [2] an implementation of QZD for a field stored in a cavity and evolving under the action of a resonant classical source. Repeated interrogation of an atom coupled to the cavity restricts the field evolution to a subspace with a photon number lower or larger than a prescribed value. This dynamics generates interesting non-classical states and can be turned into phase space tweezers to prepare nearly arbitrary quantum superposition of coherent states. We present the principle of the method and the progresses toward its experimental implementation with slow circular Rydberg atoms in a high Q superconducting microwave cavity.

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Generation of intense cw radiation with high sub-Poissonian photon statistics in the cavity-QED microlaser

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The cavity-QED microlaser, a microscopic laser based on the cavity-QED principle, now finds applications in precision measurement, quantum information and ultralow noise communication owing to its intense cw outout with nonclassical photon statistics. The sub-Poissonian photon statistics in the microlaser originates from the active photon-number stabilization due to a decreasing gain function with the photon number. Since the previous observation of Mandel Q of -0.128, many efforts were made on further improvement in system stability and detection hardware. Supersonic atomic beam at a higher oven temperature and improved cavity locking reduced the fluctuations in the interaction time and the atom-cavity detuning, which led to the more enhanced photon-number stabilization. Furthermore, we fixed the defects in the detection system, which induced a distortion in Mandel Q measurement at high photon flux. As a result, we could observe Mandel Q of -0.48, which corresponds to about 4 times larger shot-noise reduction than the previous one.

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Quantum correlated pulses from a synchronously pumped optical parametric oscillator

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Optical frequency comb with non-classical properties can be produced via parametric down-conversion of a pumping comb in a degenerate synchronously pumped optical parametric oscillator. In the time domain we developed a quantum theory of the oscillator that describes its operation both below and above oscillation threshold and gives clear insight into the character of quantum properties of an output signal comb being a train of pulses. Now we are thinking about application of a frequency comb and its non-classical counterpart for ultra-precise position sensing, particularly, in gravitational wave detectors. Here the fundamental limit on an accuracy of position determination (standard quantum limit) appears as interplay between time-arrival uncertainty of pulses and light back-action on a mechanical sub-system.

Towards ultracold fermions in a 2D honeycomb lattice

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We are setting up a new experiment with ultracold fermionic atoms in a two-dimensional honeycomb lattice to investigate intriguing phenomena which are either related to relativistic quantum physics (e.g. Zitterbewegung, Klein tunnelling) or to condensed matter physics (quantum criticality, quantum spin liquid). This system has the underlying geometry of graphene, but can be tuned and controlled in a much greater range. In the experiment, a degenerate Fermi gas of ^{6}Li will be created after laser cooling in a magneto-optical trap (MOT) and subsequent evaporative cooling in the vicinity of a Feshbach resonance in a strong optical dipole trap. The atoms will then be transferred optically into a glass cell, where they will be loaded into a two-dimensional honeycomb potential. We plan to use a site-resolved imaging technique in order to manipulate the particles and analyze their distribution in the lattice. We will show the experimental progress towards a degenerate Fermi gas.

Bosonic mixtures in a double-well trap: disorder-induced localization

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We propose a simple model of bosonic mixtures in a double-well trap to investigate the disorder-induced collapse of the phase coherence which can cause the localization of major atoms. It is found that the number of impurity atoms randomly distributed in two subwells and the inter-species interaction play an important role in the correlation of the major atoms. It strikingly shows that the delocalization can even occur when intra-species and inter-species interactions are comparable, which exhibits a ‘twonegatives make a positive’ effect. We also calculate the dependence of the compressibility on the doping ratio and inter-species interaction, and the signature of Bose glass phase is predicted. In conclusion, our studies shows that even the simple two-site BH model can be useful to investigate more interesting physics in the disordered system of ultracold atoms.

An experiment for the investigation of artificial gauge fields in ultracold Ytterbium gases

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We will present an experiment aimed at the realisation of artificial gauge fields with ultracold neutral atoms in an optical lattice [1,2]. Combining intense gauge fields with strong on-site interactions should allow to explore atomic analogs of fractional quantum Hall systems. The atomic species Ytterbium combines the advantages of a large number of both bosonic and fermionic isotopes and a long lived metastable state ($^3P_0$, lifetime 16 s), and its level scheme favours the implementation of a two-dimensional optical lattice, where the ground and excited states arrange in spatially separated sublattices. Optical coupling of the two states enables tunneling between the sublattices, resulting in a geometric phase of the atomic wavefunction equivalent to the Aharonov-Bohm phase of a charged particle in a magnetic field. We will present the first results on cooling Ytterbium atoms in our apparatus and describe the experimental techniques to implement laser-induced gauge potentials.

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Imaging and manipulating bilayer quantum gases

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Single-atom/single-site resolved experiments with ultracold neutral atoms in optical lattices offer direct access to local observables and correlation functions in strongly-interacting many-body systems. Such quantum gas microscopes have thus far been limited to investigating purely two-dimensional systems. Here, we present a scheme for single-atom/single-site resolved readout of a bilayer degenerate gas. By engineering occupation-dependent transport between two tunnel-coupled planes, our system can be used to unambiguously identify atom numbers $n = 0$ to $n = 3$ per site ("beyond parity imaging"). We obtain the first single-site resolved images of the Mott insulator shell structure with up to three atoms per site and study the formation of doublon-hole pairs across a magnetic quantum phase transition. Our technique significantly improves the imaging capabilities of quantum gas microscopes and creates new possibilities for the simulation of bilayer condensed matter systems with ultracold atoms.

Nanoplasmonic optical lattices for ultracold atoms

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Ultra-cold atoms in artificial potentials created by interfering light waves constitute a powerful tool to study strongly correlated many-body systems. However, the relevant length and energy scales are at present limited by an optical wavelength. We propose to use sub-wavelength confinement of light associated with near field of plasmonic systems to create a nanoscale optical lattice for ultracold atoms. Our approach combines the unique coherence properties of isolated atoms with the subwavelength manipulation and the strong light-matter interaction associated with nano-plasmonic systems. It allows one to considerably increase the energy scales in the realization of Hubbard models and to create effective long-range interactions in coherent and dissipative dynamics of atoms. As an example we demonstrated how these techniques can be used to prepare and study many-body states of AKLT type in the steady state of an optically driven system.

Anderson localization of Dirac fermions on a honeycomb lattice

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We study the tight-binding model with uncorrelated diagonal disorder on a honeycomb lattice. We use three independent methods: recursive Green's function, self-consistent Born approximation and time-evolution of a Gaussian wave packet, to extract scattering mean free path ℓ_s, scattering mean free time τ, density of states ρ and localization length ξ. The three methods give excellent quantitative agreement of the single-particle properties (ℓ_s, τ, ρ). Furthermore, a finite-size analysis of ? reveals that the finite-size localization lengths of different lattices and different energies (including the charge neutrality point of a honeycomb lattice) can be described by the same single-parameter curve. However, the extracted numerical value of shows great deviation from the prediction of self-consist theory of localization. Our numerical results also show possible indication of weak localization corrections.

Mobile impurities in one-dimensional cold gases: subdiffusive, diffusive and ballistic regimes

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Advances in cold gases physics are beginning to enable experiments involving the direct manipulation and observation of single- or few-atom mobile impurities [1] within a many-body quantum system, a topic of longstanding interest for condensed matter theory, where it is related to studies of e.g. conductivity and the X-ray edge problem. Further progress in this direction is expected from the latest generation of experiments offering single-site addressability in optical lattices [2, 3] .

In light of these developments we study the dynamics of mobile impurities in 1D quantum liquids using a DMRG technique. We address the recently proposed subdiffusive regime of impurity motion [4], a class of excitations beyond those described by the standard Tomonaga-Luttinger theory. We study the conditions for observing this regime and its' crossover to the ballistic regime. We furthermore examine the possibilities to observe the intermediate diffusive motion of impurities in these systems.

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Collisions involving nD + nD Rydberg states in a dipole trap

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We have studied nD + nD multilevel pairwise interactions between Rydberg atoms in a magneto-optical trap, and our results have shown that the electric field plays an essential role in the interaction dynamic [1,2]. In this work, our goal is to study the nD + nD interaction in a higher density cold sample in a dipole trap. Therefore, we have loaded a QUEST trap for Rb using a CO_2 laser. The dipole laser beam is focused to a spot size ($1/e^2$) around 70 µm. For 75 W laser power, the QUEST depth is ~ 730µK and the density sample is arround $4x10^{11}$ atoms/cm^3. The nD Rydberg states are excited using a CW blue light (480nm) with 1MHz of linewidth. During the presentation we will show our first results on the nD + nD interactions in a CO_2 optical trap.

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Controlled optical collisions in a metastable neon MOT

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We present the results for controlled optical collisions of cold, metastable neon atoms in a magneto-optical trap [1]. The modification of the ionizing collision rate is demonstrated using a control laser tuned close to the $(3s)^3P_2$ to $(3s)^3D_3$ cooling transition. The measured ionization spectrum excludes resonances as a result of the formation of photoassociated molecules connected to the $\Omega = 5$ excited potential as predicted by Doery et. al [2]. Instead, we observe a broad unresolvable ionization spectrum that is well described by the established theory of Gallagher and Pritchard[3]. Depending on the frequency detuning of the control laser relative to the cooling transition, for a red frequency detuned laser beam we have measured up to 4 x enhancement of the ionization rate. In the case when the control laser us detuned to the blue of the cooling transition we observe optical shielding and a reduction in the ionization rate of up to a factor of 5. We will present the results of this investigation.

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Radiative double-electron capture by bare nucleus with emission of one photon

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Calculation of the cross-section for the process of double-electron capture by a bare nucleus with emission of a single photon is presented. The double-electron capture is evaluated within the framework of quantum electrodynamics. The line-profile approach is employed. Since the radiative double-electron capture is governed by the electron correlation, corrections to the interelectron interaction were calculated with high accuracy, partly to all orders of the perturbation theory. The calculations of the cross-section are presented not only for the experiments [1, 2, 3] as it was also shown in [4] but for new experiments F^{9+} + C and Cr^{24+} + He / N_2 ions. Also we investigate the dependence of the cross-section from the energy of incoming ion are presented.

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Micromotion in trapped atom-ion systems

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We examine the influence of the ion micromotion on the controlled collision of a trapped atom and a single trapped ion. Using the transformation of Cook *et. al.* we find that the micromotion can be represented by two periodically oscillating operators. In order to study their effect, we calculate (i) the coupling strengths of the micromotion operators by numerical integration and (ii) the quasienergies of the system by applying the Floquet formalism — a useful framework for studying periodic systems. It turns out that the micromotion is not negligible when the distance between the atom and the ion traps is shorter than a characteristic distance. Within this range the energy diagram of the system changes remarkably when the micromotion is taken into account, which leads to undesirable consequences for applications that are based on an adiabatic collision process of the trapped atom-ion system. We suggest a simple scheme for bypassing the micromotion effect in order to successfully implement a quantum controlled phase gate proposed previously, and create an atom-ion macromolecule. The methods presented here are not restricted to trapped atom-ion systems and can be readily applied to studying the micromotion effect in any system involving a single trapped ion.

Atomic interactions… Mo-154

Cooperative interactions in nanometre-thickness thermal Rb vapour

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Similar to cavity QED, the reflection of the field by neighbouring dipoles in a dense medium gives rise to a cooperative enhancement of the atom-light interaction. Such cooperative effects manifest as a of the decay rate (super- or subradiance) and a shift of the resonance known as the cooperative Lamb shift. By tuning the atomic density and layer thickness of a nanometre-scale atomic vapour cell, we are able to move continuously from negligible to dominant dipole–dipole interactions, and experimentally measure these cooperative effects including the cooperative Lamb shift, in agreement with theoretical predictions of nearly 40 years ago [1,2]. Finally we report on recent results on the propagation of light in the cooperative limit where the effects of superradiance and slow or fast light are combined.

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Electron spin waves in atomic hydrogen gas

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We present a high magnetic field study of electron spin waves in atomic hydrogen gas compressed to high densities of ~ 10^{18} cm^{-3} at temperatures 0.26 - 0.6 K [1]. We have observed a variety of spin wave modes caused by the collisionally induced identical spin rotation effect with strong dependence on the spatial profile of the polarizing magnetic field. We demonstrate confinement of these modes in regions of strong magnetic field and manipulate their spatial distribution by changing the position of the field maximum. At high enough densities a sharp and strong peak appears in the ESR spectrum, originating from the spin wave modes trapped in magnetic field maximum. This is accompanied by spontaneous coherence of the transversal magnetization, similar to that of the homogeneously precessing domain in liquid ^{3}He, where this can be interpreted as Bose-Einstein condensation of magnons [2].

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Precision measurement of *s*-wave scattering lengths in ^{87}Rb

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We use collective oscillations and trapped Ramsey interferometry of a two-component Bose-Einstein condensate of ^{87}Rb atoms (states $|1> \equiv |F = 1, m_F = -1>$ and $|2> \equiv |F = 2, m_F = 1>$) for the precision measurement of the interspecies scattering length a_{12} and the intraspecies scattering length a_{22}. We show that in a cigar-shaped trap the 3D dynamics of a component with a small relative population can be conveniently described by a 1D Schrödinger equation for an effective harmonic oscillator. The frequency of the collective oscillations is defined by the ratio a_{12}/a_{11} and is largely decoupled from the scattering length a_{22}, the total atom number and two-body loss terms. By fitting numerical simulations of the coupled Gross-Pitaevskii equations to the recorded temporal evolution of the axial width we obtain the value $a_{12} = 98.006(16)a_0$, Using Ramsey interferometry of the two-component condensate we measure the scattering length $a_{22} = 95.44(7)a_0$.

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Rb resonance spectroscopy in a random porous medium

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We have studied the transmission spectrum of Rb atomic vapor confined inside the intersticial cavities of a random porous medium. The medium, made of compacted ground pyrex glass, with approximately 50 μm mean grain size, fills one end of a closed cylindrical Rb vapor spectroscopic cell. The porous sample strongly diffuses light with a diffusion distance $D \lesssim 1$ mm. We detected laser light frequency scanned around the Rb D1 transitions that has traversed several millimeters of the porous sample. Using fast time-resolved detection, synchronized to a sudden change in laser intensity, we were able to identify the contribution to the transmitted light of photons being spontaneously emitted by the Rb atoms. For low atomic densities, the randomness of the photon trajectories in the sample results in an "integrating sphere" effect in which the re-emission of light almost cancels the atomic absorption. At large atomic densities, the contributions of absorption and spontaneous emission to the transmission present noticeable spectral differences. Also, as the atomic density is increased, the characteristic decay time of the spontaneously emitted photons increases and the fraction of absorbed energy being re-emitted decreases. We interpret these observations as due to the onset of photon trapping in connection with non-radiative decay in atom-wall collisions.

Casimir-Polder interaction between ultracold atoms and a carbon nanotube

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Interfacing cold atom clouds and nanostructures, especially carbon nanotubes has been attracting large interest because the objects have similar atom numbers and masses. This enables both mechanical and electronic manipulation of solids by atoms and vice-versa. In our experiment, we bring ultracold atom clouds of rubidium into spatial overlap with a free standing carbon nanotube thus atoms are scattered on the tube. We observe the time dependent atom loss from thermal clouds and Bose-Einstein condensates, from which we derive the Casimir-Polder interaction potential [1]. We identify the scattering radius and the regimes of quantum mechanical scattering between rubidium atoms and the carbon nanotube. We report on the technique of "cold-atom scanning probe microscopy" [2] for imaging the topography of nanostructures and for ultrasensitive force measurements.

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Importance of correlation – polarization and PCI in Electron Impact single ionization of Xe atom

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The charged particle impact ionization studies of fundamental atomic and molecular systems have been of great interest since the early days of quantum mechanics. Extensive theoretical and experimental investigations have been carried out to understand the electron impact single ionization (i. e. (e, 2e) processes) of various targets (see [1] and references cited therein). Accurate cross sections for Xe atom target ionization by electron impact are very important for the understanding of the complex interactions involved in the plasma processes. We will report triple –differential cross section of Xe atoms for low energy (e, 2e) ionization at the incident electron energies ranging from 5 to 40 eV above the ionization threshold from coplanar to perpendicular plane geometries in the modified distorted wave Born approximation formalism. We will discuss the effect of target polarization and post collision interaction in coplanar as well as the perpendicular plane geometrical conditions. We will also compare the result of our calculation for Xe with the very recent measurements of Nixon *et al.* [2].

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Influence of three-body interactions on Rb fine-structure transfer in inert buffer gases

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We will present measurements of the mixing rates and cross sections for collisional excitation transfer between the $5P_{1/2}$ and $5P_{3/2}$ states of rubidium in the presence of inert buffer gases. Selected pulses from a high repetition rate, mode-locked ultrafast laser are used to excite either Rb state with the fluorescence due to collisional excitation transfer observed by time-correlated single-photon counting. The measured mixing rates exhibit a linear dependence on the buffer gas density at low pressures, but include a significant quadratic component at buffer gases densities greater than 1 atm. We attribute this quadratic component to three-body interactions which alter the collisional transfer cross section by reducing the fine-structure splitting between Rb 5P levels. We examine this effect for a range of buffer gas temperatures and pressures[1] along with mixtures such as Rb-He-Ar.

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Investigation of temperature behaviour of alkane- and alkene-based anti-relaxation coatings of caesium vapour cells

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The temperature (294° K < T < 340° K) dependence of the longitudinal (T_1), transverse (T_2) relaxations times and atoms absorption rate were experimentally investigated for two cells with alkane- and alkene-based coatings. The $T_1(T)$ and $T_2(T)$ were measured by Franzens "relaxation in the dark" and double radio-optical resonance method accordingly. Both cells showed a growth of T_1 to a certain temperature (T = 332° K for alkane- and T = 298° K for alkene-based coatings), after which the T_1 decreased rapidly. T_2 has a monotone decrease for alkane- and does not change for alkene-based coatings in a whole measured temperature range. The concentration of Cs atoms in bulb was monitored by measuring of transmitted through the cell light intensity after quick closing of the valve between bulb and Cs reservoir for studying of atoms absorption rates [1]. Different character temperature dependence of slow and fast components of characteristic time for alkane- and alkene-based coating were found.

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Inelastic confinement-induced resonances in low-dimensional quantum systems

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Ultracold atomic systems of reduced dimensionality show intriguing phenomena like fermionization of bosons in the Tonks-Girardeau gas or confinement-induced resonances (CIRs) which allow for a manipulation of the interaction strength by varying the trap geometry. Here, a theoretical model is presented describing inelastic confinement-induced resonances which appear in addition to the regular (elastic) ones and were observed in the recent loss experiment of Haller et al. in terms of particle losses [1]. These resonances originate from possible molecule formation due to the coupling of center-of-mass and relative motion. The model is verified by ab initio calculations and predicts the resonance positions in 1D as well as in 2D confinement in agreement with the experiment. This resolves the contradiction of the experimental observations to previous theoretical predictions.

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On the photoionization cross section in Rydberg states: possible evidence of Cooper minina

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Rydberg atoms have as one of their characteristic the high principal quantum number. Their large dimensions imply in a large dipole moment, which allows one to use them for studies of atomic interactions with electromagnetic fields, including processes of photoionization. The increasing attention given to the investigation of photoionization cross sections of these highly excited atoms, is due to its importance to several areas like Atomic and Molecular Physics, Astrophysics, Plasma Physics, among others. Based on the model proposed by Aymar and co-workers [1] we studied the photoionization cross sections of alkali atoms, expanding the previous analysis to $n \geq 44$. Furthermore, the photoionization cross sections for the ground state are well known (both theoretically and experimentally [1], but the same is not true for the excited states. We performed an analysis of the behaviour of radial wave functions depending on the photoelectron energies and by analysing them we have alsoperformed a study of the Cooper minima.

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Study of Rydberg EIT in ultracold atoms across the BEC transition

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Electromagnetically induced transparency (EIT) involving Rydberg states [1] has become the subject of interest in cold atom experiments due to a wealth of possible applications ranging from quantum computing to mediated photon-photon interactions [2]. We study the behaviour of Rydberg EIT in an ensemble of ultracold ^{87}Rb as it is cooled through the transition to Bose-Einstein condensation. We observe the familiar dipole blockade as a function of atom density and find good agreement between the experimental scaling of the blockade radius and theory. No discontinuous behaviour is observed as the gas is cooled through the BEC phase transition. By realizing Rydberg EIT in condensates we will be capable of studying the strong nonlinear interactions introduced by the effect in ultracold, dense atomic gases.

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Chaos-induced enhancement in electron recombination in highly charged ions

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We developed a statistical theory for the resonant multi-electron recombination based on properties of chaotic eigenstates [1]. Level density of many-body states exponentially increases with the number of excited electrons. When the residual electron-electron interaction exceeds the interval between these levels, the eigenstates become "chaotic" superposition of a large number of Hartree-Fock determinant basis states. This situation takes place in some rare-earth atoms and majority of multiply-charged ions excited by the electron recombination. We derived a formula for the resonant multi-electron recombination via di-electron doorway states leading to such compound resonances and performed numerical calculations for the electron recombination with tungsten ions W^{q+}, q = 17 – 24. A recent experiment [2] showed that the electron recombination of tungsten ion W^{20+} exceeds the theoretical direct recombination by three order of magnitude. Our calculations agree with this experimental result.

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Ultracold atom-ion collisions in mixed dimensions

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We study ultracold collisions in a model 1D system formed by a free atom and a trapped ion. This model describes motion in a waveguide with spacing between transverse modes much larger than both the ion trap level spacing and the collision energy. We consider a zero-range atom-ion interaction, appropriate to model the effect of the interatomic potential in loose traps. We investigate two situations: static harmonic trapping and time dependent rf-trapping (Paul trap) of the ion.

The static case is numerically treated using two approaches. The integral equation of scattering is solved by a spectral method adapted to treat the kernel singularity. The close coupled form of the Schrödinger equation is solved using a log-derivative propagation approach to obtain directly the S-matrix. Coupling between center of mass and relative motion results in nontrivial resonance effects. The molecular states associated to the resonances are identified based on numerical bound level calculations. In the case of time-dependent rf-trapping, we use the Floquet theorem to convert the problem to a time independent formulation. The sparse linear system resulting from a high order finite element representation of the time-independent Hamiltonian issolved using available computer packages. We investigate the energy exchange between atom and ion, assessing the influence of the ion micromotion on the collision process. Our model could be applied to interpret results of current atom-ion experiments (1,2).

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Identification and non-destructive state detection of molecular ions

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Cold molecules have a multitude of applications ranging from high resolution spectroscopy and tests of fundamental theories to cold chemistry and, potentially, quantum information processing. Prerequisite for these applications is the cooling of the molecule's motion and its non-invasive identification. Futhermore, the internal state of the molecule needs to be prepared and non-destructively detected.

We have developed a novel technique to measure the average charge-to-mass ratio of trapped ions with high precision through broadband excitation of the ions' centre-of-mass mode motion and subsequent detection of the Doppler induced fluorescence modulation [1]. Chemical reactions between neutral molecules/atoms and trapped molecular ions can be investigated using this method by analysing the fluorescence of atomic ions which are trapped alongside the molecular ions. Due to the precision of this method, reaction rates and branching ratios can be measured even with large ion crystals (up to 100 ions).

The non-destructive state detection of trapped molecules is still beyond current experiments. Employing state selective laser induced dipole forces, we aim to detect the internal state of molecular ions by mapping the state information onto the ions' motion.

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Vibrational quantum defect coupled to improved LeRoy-Bernstein formula for a precise analysis of photoassociation spectroscopy

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Laser photoassociation (PA) of cold atoms creates excited, weakly-bound molecules, which are key intermediates in the most of schemes that allow the formation of cold molecules in the ground state. For that reason the spectroscopy of these weakly bound molecules is one of the tools to know, not only the energy position of the levels but also if it exists their mixings with neighboring levels. Indeed, the mixings determine the wavefunction shapes, especially at short internuclear distance, and thus the Franck-Condon factors required for molecule formation. We show that, for an accurate analysis of the PA spectroscopy data, the LeRoy-Bernstein formula has to be improved [1]. Furthermore we show that the use of vibrational quantum defects and of Lu-Fano graphs provide efficient tools to determine and measure the couplings [2, 3, 4].

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A study of cold ion-polar molecule reactions between sympathetically cooled molecular ions and slow polar molecules

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Cold ion-polar molecule reactions play important roles in the synthesis of intersteller molecules [1]. Even though the chemical reactions in dark interstellar clouds occur at very low temperatures, most of the reaction-rate constants in the astronomical database were measured at room temperature. Here we have developed a setup to directly measure cold ion-polar molecule reactions. We extended the experiment in Ref. [2] to the rate measurement between sympathetically cooled molecular ions and velocity-selected slow polar molecules. In fact we have successfully determined the reaction rate of $N_2H^+ + CH_3CN \rightarrow CH_3CNH^+ + N_2$ at very low temperatures. The results and a discussion of this research will be presented.

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Cold neutral… Mo-170

Ultralong-range Rydberg molecules

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We report on our recent experiments exploring ultralong-range Rydberg molecules. These unusual bound states between Rydberg atoms and ground state atoms feature novel binding mechanisms based on low energy electron scattering as well as internal quantum reflection at a shape resonance of electron-atom scattering [1]. Besides the binding energies of dimer and trimer states, further properties are studied in high resolution spectra in the high density regime. This extends from density dependent lifetime measurements to experiments in electric fields that reveal a molecular Stark effect due to a permanent electric dipole moment of the molecules [2].

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Hyperfine structure of RbCs excited molecules

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Unlike ground state alkali-metal diatomics, very little is known about the hyperfine structure of excited electronic states. We present a preliminary analysis of the expected hyperfine structure of the rovibrational levels of the RbCs excited electronic states correlated to the lowest $^2S + {}^2P$ limit, based on an asymptotic model for the hyperfine hamiltonian. We set up potential curves built on long-range atom-atom interaction connected to short-range ab initio results obtained in our group. The hyperfine structure strongly depends on the projection of the total angular momentum of the molecule, and on the sum of projections of the total angular momentum of the separated atoms.

Theory of mixed-field orientation for linear molecules: loss of adiabaticity

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We present a theoretical study of the mixed-field-orientation experiments of linear molecules, where a strong degree of orientation is obtained by means of a long linearly polarized laser pulse and a weak electric field [1]. We solve the corresponding time-dependent Schrödinger equation in the rigid rotor approximation, taking into account the time profile and the spatial distribution of the alignment pulse. Our non-adiabatic model reproduces the experimental observations for the OCS molecule [2]. We show that the adiabaticity of the mixed-field orientation depends on the avoided crossings that the states suffer and on the formation on the quasidegenate doublets in the pendular regime. For the first time, we show that the mixed field orientation is, in general, non-adiabatic being mandatory a time-dependent description of this process, and redefine the meaning of adiabatic conditions in these experiments [2].

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Towards a Bose-Einstein condensate of ground-state molecules in an optical lattice

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Ultracold molecules trapped in an optical lattice at high density and prepared in their lowest internal quantum state are an ideal starting point for fundamental studies in physics and chemistry, ranging from novel quantum gas experiments and cold controlled chemistry to quantum information and quantum simulation.

In our experiment, we create ultracold and dense samples of molecules in their internal ground state in an optical lattice. We load a Bose-Einstein condensate of Cs atoms into the optical lattice potential and drive the superfluid-to-Mott-insulator transition under conditions that maximize double-site occupancy and efficiently create weakly bound Cs dimer molecules on a Feshbach resonance. These are subsequently transferred to a specific hyperfine sublevel of the rovibronic ground state by a coherent optical 4-photon process with the Stimulated Raman Adiabatic Passage (STIRAP) technique while each molecule is trapped in the motional ground state of an individual optical lattice well. We have implemented a series of technical improvements for optimized transfer efficiency and now aim at producing Bose-Einstein condensates of ground-state molecules by adiabatically removing the optical lattice potential.

Statistical evaluation of ultracold molecular fraction rate

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In recent years, various ultracold molecule production experiments have been carried out. Molecules are formed via a field ramp through a Fano-Feshbach resonance (FFR). They are subsequently transferred to the rovibrational ground state by STIRAP with very high efficiency. In this scenario, the final molecule conversion rate is restricted by the FFR fractional conversion. We study the FFR molecular fractional conversion rate using a Monte Carlo simulation based on the stochastic phase space sampling (SPSS) model[1]. The key idea of SPSS is that the phase space volume of atomic pairs does not change during an adiabatic magnetic sweep. We have applied this method to Fermi-Fermi, Bose-Bose, and Bose-Fermi cases, and have compared our SPSS result with that of the equilibrium theory[2]. We have identified some differences between results of the two approaches, especially in ultracold regions that have not yet been experimentally realized.

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Ro-vibrational cooling of molecules. Towards Sisyphus cooling of molecules

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One of the greatest challenges of modern physical chemistry is to push forward the limits of electromagnetic or laser techniques to probe or manipulate molecules at low temperatures where molecular interactions are dominated by pure quantum phenomena. Following our pioneer work [1] we present our recent development concerning the rotational and vibrational cooling of the formed molecules: we are now able to transfer Cs_2 molecules into a single ro-vibrational level (including v = 0, J = 0) of the singlet ground electronic state. Combined with Sisyphus cooling, this method is probably able to produce a large sample of molecules at sub-mK temperature. The principle of Sisyphus cooling of molecules can be described in three steps: 1) removing kinetic energy through a motion in an external potential, 2) dissipative process preventing the reverse motion, 3) repetition of the "one-way" (or "single photon") process by bringing back the molecules to the initial state.

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The spectroscopy and MOT for neutral mercury atoms

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Due to less blackbody radiation shifts, mercury atoms are regarded as one of the best candidates for optical lattice clock [1]. Here we report our recent progress towards laser cooling and trapping of mercury atoms for the ultracold sample ofoptical lattice clock. Several spectroscopies, including saturated absorption spectroscopy (SAS), DAVLL spectroscopy and frequency modulation (FM) spectroscopy, were investigated for the frequency discrimination and stabilization of the $^1S_0$-$^3P_1$ UV cooling laser. The ultra-high vacuum system of 3×10^{-9} Torr was designed and installed with the mercury source cooled by multi-stage-TEC. The ^{202}Hg atoms were trapped in the MOT, with the folded configuration by one beam cooling laser [2], and 2×10^6 atoms were detected by fluorescence method.

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Transfer cold atoms from the time-averaged orbiting potential to an optical dipole trap

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We constructed an optical dipole trap (ODT) for rubidium-87 atoms with a 5W multimode Nd:YAG fiber laser. The beam waist of the focused laser beam is approximately 22 μm and the ODT has a trap depth of about 290 μK. The atoms were first cooled and compressed in the time-averaged orbiting potential trap (TOP) by ramping down the rotating magnetic field amplitude. At the end of the process, there were 4×10^{7} atoms with a peak density above 1×10^{11} cm^{-3} and a temperature below 60 μK in the TOP. These atoms were transferred from the TOP to the ODT. We will report the studies of transfer efficiency and the temperature and lifetime of the trapped atoms in the ODT.

Preparing well-defined atom-number states in the evanescent field of an optical nanofibre

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We present a scheme where the evanescent field around a sub-wavelength diameter tapered optical nanofibre is combined with an optical lattice. We show that when the fibre is aligned perpendicularly to the transverse plane of a two-dimensional optical lattice, the evanescent field around the fibre can be used to create a time-dependent potential which melts the lattice potential locally. We first describe the disturbance of the lattice due to scattering of the lattice beams on the fibre and then show how the attractive van der Waals potential close to the surface can be compensated by a repulsive blue-detuned evanescent field. This scheme allows access to a regime in which a small number of atoms can be locally addressed without disturbing the rest of the lattice. If the environment around the fibre is given by a Mott-Insulator state, the melting of the lattice transfers a well-defined number of atoms into the fibre potential. The resulting state is therefore an atom-number state and can be used for applications in quantum information. We also investigate another application of our system; using the fibre as a way of measuring the fidelity of the Mott Insulator state. By considering spontaneous emission of the atoms trapped in the lattice into the guided modes of the fibre as it passes close by, it is possible to determine whether specific sites are occupied or unoccupied.

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High-optical-depth cold cesium gases for quantum optics experiments

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Many quantum optics experiments can benefit from cold atomic media with high optical depths, such as low-light-level nonlinear optics [1,2], high efficiency and capacity quantum memory [3,4], high-generation-rate photon pairs [5], and simulating quantum many-body physics with strongly-interacting photons [6]. We have combined the techniques of two-dimensional magneto-optical trap (MOT), dark and compressed MOT, and optical pumping to routinely obtain cold atomic samples with optical depths of ~200 for the $F=3 \rightarrow F=4$ transition of cesium D_2 line. Attempts to achieve even high optical depths are underway and the results will be presented.

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Integrated magneto-optical traps on a chip using micro-fabricated gratings

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We have integrated magneto-optical traps (MOTs) into an atom chip which is able to cool and trap ~ 10^7 atoms directly from a thermal background of ^{87}Rb. Diffraction gratings are used to manipulate the light from a single input laser to create the beams required for a MOT[1]. The gratings are etched into the surface of a silicon wafer by either electron beam, or photo-lithography making them simple to fabricate and integrate into other atom chip architectures. Unlike previously integrated cold atom sources on a chip [2] the atoms now sit above the surface where they can be easily imaged, manipulated and transferred into other on-chip potentials. These devices significantly simplify the initial capturing of atoms, representing substantial progress towards fully integrated atomic physics experiments and devices. They also offer a simple way to integrate many atom sources on a single device.

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High-performance apparatus for simultaneously laser cooling of ^{87}Rb and ^{6}Li

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The RbLi molecule is a promising candidate for exploring novel quantum phases of ultracold molecules owing to the relatively large electric dipole moment (4.2 Debye). We developed an apparatus for simultaneous laser cooling of ^{87}Rb and ^{6}Li for the purpose of creating fermionic RbLi molecules. We exploited separate Zeeman slowers for each species, which were attached to a stainless-steel chamber kept at ultra-high vacuum ($<10^{-11}$ Torr). The capture velocities for Rb and ^{6}Li are 300 m/s and 800 m/s, respectively. We performed Doppler-free polarization spectroscopy of Li in a heat-pipe oven for laser frequency stabilization. We found that the Ar buffer gas enhances the polarization signal, which is explained by a simple model considering velocity-changing collisions [1]. We could simultaneously collect 10^{9} Rb atoms and 10^{8} Li atoms in a magneto-optical trap. We also developed magnetic coils which offer a uniform magnetic field of about 1100 G for producing Feshbach molecules.

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Tuneable microwave sidebands by optical injection in diode lasers

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Optical injection in diode lasers can produce frequency tuneable sidebands[1]. We show that by carefully tailoring the frequency and intensity of the injection laser relative to the free running laser we can create narrow sidebands suitable for atomic physics experiments. We observe a frequency tuning range which exceeds the modulation bandwidth of the free running laser. Our detection bandwidth limits this measurement to a range of about 20 GHz, but the tuning range is predicted to be as wide as the longitudinal mode spacing of the diode laser[2] which can be of the order of 100 GHz. The sideband intensity can also be controlled by the injection. The output of a laser with this injection can be used to simultaneously address two transitions in common alkalis or small heteronuclear molecules. We demonstrate the frequency stability of the sidebands by magneto-optical trapping of rubidium using light from the injected laser only[3]. We propose further applicationsof the sideband technique.

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Isotope shifts of natural Sr^+ measured by laser fluorescence in sympathetically cooled Coulomb crystal

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We measured by laser spectroscopy the isotope shifts between natural even-isotopes of strontium ions for both the $5s^2S_{1/2} \rightarrow 5p^2P_{1/2}$ (violet) and the $4d^2D_{3/2} \rightarrow 5p^2P_{1/2}$ (infrared) optical transitions. The fluorescence spectra have been obtained by simultaneous measurements on a two-species Coulomb crystal in a linear Paul trap containing $\sim 10^4$ laser-cooled Sr^+ ions. The isotope shifts are extracted from the experimental spectra by fitting the data with the solution of the optical Bloch equations describing a three-level atom in interaction with two laser beams. This technique allowed us to increase the precision with respect to previously reported data. The results for the $5s^2S_{1/2} \rightarrow 5p^2P_{1/2}$ transition are $\nu_{88} - \nu_{84} = +378(3)$ MHz and $\nu_{88} - \nu_{86} = +170(2)$ MHz. In the case of the unexplored $4d^2D_{3/2} \rightarrow 5p^2P_{1/2}$ transition we find $\nu_{88} - \nu_{84} = +822(6)$ MHz and $\nu_{88} - \nu_{86} = +400(2)$ MHz. These results provide more data to a stringent test for theoretical calculations of the isotope shifts of alkali-metal-like atoms [1].

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Injecting, extracting, and velocity filtering neutral atoms in a ring dipole trap

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Ring traps for cold-atom physics can be foreseen as the low-energy counterpart of circular accelerators in high-energy physics. In this regard, we discuss here a coherent technique to inject, extract, and velocity filter neutral atoms in a ring dipole trap coupled to two additional dipole waveguides, by extending our previous work [1] to waveguides. By adiabatically following a particular transverse energy eigenstate of the system, the transverse spatial dark state, the proposed technique is shown to allow for an efficient and robust velocity dependent atomic population transfer between the ring and the input/output waveguide. We have derived analytical conditions for the adiabatic passage as a function of the atomic velocity along the input waveguide as well as on the initial population distribution among the transverse vibrational states. The performance of our proposal has been checked by numerical integration of the corresponding 2D Schrödinger equation with state of-the-art parameter values for a ring dipole trap with Rubidium atoms.

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Magnetic traps for cold atoms based on circular superconducting micro-structures

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We design magnetic traps for neutral atoms with the fields generated by supercurrents imprinted in type-II superconducting disks and rings. We simulate the current density distributions in these superconducting structures under different loading fields bymeans of the critical state method [1] and compute the resulting external magnetic fields with Biot-Savart theorem. The spatial inhomogeneous magnetic fields can be used to trap cold atoms with or without additional bias fields. Versatile supercurrent-patterns can be written in the superconducting disks and rings by programmable loading fields, which may lead to variable trapping potentials. We analyze in detail the quadrupole traps, self-sufficient traps and ring traps generated by the supercurrents written in the superconducting disks and rings. The absent of the transport currents and bias fields may reduce the noise from the power source. The ease of creating the ring traps and the low noise for trapping atoms make the circular superconducting structures attractive for atom chip interferometers.

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Laser cleaning and background-free detection in microfabricated ion traps

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We present recent work on laser cleaning of a microfabricated surface ion-trap. A particular problem in such traps is heating of the ion by electric field noise, which scales as $\sim d^{-4}$ with ion-surface distance d. Pulses from a 355nm frequency-tripled Nd:YAG laser were used to ablate surface adsorbates which reduced the heating rate by a factor of ~ 2, and changed its frequency dependence. This was the first experimental demonstration of in-situ reduction of an ion trap heating rate [1].

We also describe a Doppler cooling and detection scheme for ions with low-lying D levels which suppresses scattered laser light background (count rate 1 s^{-1}), while retaining a high fluorescence signal (29000s^{-1}) [2]. This scheme is useful for experiments where ions are trapped near surfaces.

Finally, we present data characterizing a three-dimensional microstructured gold-on-alumina ion trap. The chip has a cross-shaped trapping region with four individual trap arms connected by a central junction.

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New developments in high power narrow linewidth fiber amplifiers for atomic physics

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We present an overview of the recent progress in the narrow linewidth, high power fiber amplifiers, including progress on single frequency fibers operating at wavelengths outside the common 1064nm wavelength and at high power levels. Such high power sources can be utilized for efficient loading of Far-Off-Resonant-Traps (FORT) from MOT. Excellent beam quality, low noise and robust all-fiber designs that do not need realignment during the lifetime of the device are some of advantageous of fiber based sources. Examples of the latest results to be presented include, development of high power fiber amplifiers operating at output powers of ~ 1 kW, achieved through phase modulation of single frequency fiber sources to overcome SBS limitations. The latest results on GHz linewidth sources amplified to kW power levels will be presented along with novel architectures such as a remote amplifier head that simplify the use of the technology.

The adoption of active polarization control technology has enabled non-PM fiber amplifiers to operate with 17dB PER, eliminating the need for expensive PM components in the fiber amplifier chain. The use of Tm-doped fiber lasers and amplifiers at wavelengths around 2000nm will be presented including high power wavelength tuning results and high power single frequency amplification. Frequency doubling of narrow linewidth fiber sources is an attractive method to generate new wavelengths that are of interest for AMO community. Results of simple external frequency doubling using commercially available PPLN material for creating 532 (nm) with output power > 10 (W) will be presented.

An experimental setup for implementing graph states with Rydberg atoms

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Utracold, neutral atoms are a potentially scalable platform to physically implement quantum information processing schemes. We have identified a specific experimental set-up as being especially well-suited to the implementation of the “one-way” model of quantum computation. The set-up includes a high numerical aperture lens and a spatial light modulator to create tightly focussed optical dipole traps that can be arbitrarily placed within the two-dimensional focal plane of the lens. For our particular case, a tetrahedral MOT design is particularly appealing, as it requires limited optical access whilst using low power coils for the quadrupole magnetic field. We present a special case of 4-beam MOT operating at very acute angle, which allows to cool atoms to temperatures of order 40μK. Atoms are then loaded into our tightly focused dipole trap. Ultracold atoms loaded into these traps can be laser-excited to Rydberg states that have strong, long-range, controllable interactions. The controllability of these interactions and the controllability of the geometry of the traps give us a highly versatile set-up to investigate the creation of multiparticle entangled states, including the “graph states” that are the starting point of the one-way model of quantum computation.

Bose-Einstein condensation of ytterbium for quantum information and simulation

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We report on the progress of the new experiment for cooling and trapping of atomic Ytterbium at LENS, University of Florence. The current setup includes a thermal Ytterbium atomic beam source, a Zeeman slower operating on the ${}^1S_0 - {}^1P_1$ transition, and a chamber for the MOT (using the ${}^1S_0 - {}^3P_1$ transition) with an in-vacuum optical Fabry-Pérot cavity to implement a FORT trap. We have achieved a BEC of bosonic ^{174}Yb in a crossed dipole trap and are currently working with the fermionic ($I = 5/2$) ^{173}Yb species. The goal is to load the ultra-cold atoms into a single layer, 2D optical lattice. There quantum simulations will be performed and the atoms will be manipulated individually to implement quantum computing operations. The ultra-narrow clock transition ${}^1S_0 - {}^3P_0$ will serve as an important tool for high-fidelity state manipulation and an appropriate laser system is developed and presented. Readout will be done via single site imaging by a high resolution objective lens.

An integrated fiber-trap for ion-photon quantum interface

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The controlled emission and absorption of single photons is an important enabling technology in the fields of quantum communication, cryptography and computing. We have realized a novel photonic system that tightly integrates optical fibers and a state-of-art ion trap [1]. The optical fibers not only work as photonic channels but their metallic jackets also provide a trapping electric field for the ion. This allows us to bring the fibers to within approximately 300 μm of the trapped ionwithout disturbing the trapping field. With a single cold ion trapped between the end facets of the two fibers, we are able to efficiently collect the ion's fluorescence using no further optics. Strong photon anti-bunching is observed in both the fluorescence from continuous excitation of the ion, and from pulsed excitation, where we are able to generate a pulse train of single photons with a defined temporal shape. The scheme can be extended to implement a coherent ion-photon interface through strong coupling cavity QED.

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Anderson localization of molecules in quasi-periodic optical lattices

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We investigate the formation of molecules made of two interacting atoms moving in a one dimensional bichromatic optical lattice. We derive the quantum phase diagram for Anderson localization of molecules as a function of interaction and the strength of the external potential. We show that the localization transition has fingerprints in the quasi-momentum distribution of molecules. When single particle states show multi-fractal behavior, the binding energy of molecules is found to exhibit an anomalous scaling exponent as a function of the interaction strength.

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Calculation of bound states of anisotropic potentials for the Schrödinger equation in two dimensions

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Bound states of the Schrödinger equation in two dimensions for anisotropic potentials $\lambda V(\vec{r})$ are considered, where λ is a dimensionless coupling strength. Simon [1] studied shallow bound states with energies $E \to 0$ and couplings $\lambda \to 0$. Here, the methods of Ref. [1] are used to obtain exact integral equations for the energies and wavefunctions, for any energy and any coupling strength λ. The equations contain some freedom of choice which can be used to improve convergence. The expressions simplify if $V(\vec{r})$ has some symmetry. In the isotropic case, this reduces to what was obtained using the Jost function formalism [2]. Practical applications of the formulas for the calculation of bound-state energies are discussed.

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Pairing in a few-fermion system with attractive interactions

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We have studied few-particle systems consisting of one to six fermionic atoms in two different spin states in a 1D harmonic potential. We tune the strength of the attractive interaction between the particles using a Feshbach resonance and probe the systemby deforming the trapping potential and observing the tunneling of particles out of the trap. We find that the timescale of the tunneling process increases as a function of interaction strength. For even particle numbers we observe a tunneling behavior which deviates from uncorrelated single particle tunneling indicating the existence of pair correlations in the system. From the tunneling timescales of the systems we infer the binding energies for different particle numbers which show a strong odd-even effect, similar to the one observed in nuclei.

Pseudospin Hubbard model on the honeycomb lattice: a path-integral approach in the strong-coupling regime

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Quantum MC simulations for correlated electrons on a honeycomb lattice (graphene's lattice) [1] showed the presence of a quantum spin liquid phase between the usual semi-metal phase and an antiferromagnetically ordered Mott insulator phase, i.e., for intermediate strength interactions. Also, it was argued that in graphene the "electron's pseudospin" corresponds to a real angular momentum [2]. In this scenario, we present a path-integral approach for the pseudospin Hubbard model on the honeycomb lattice in the strong-coupling regime, in which case we show that the degrees of freedom of the Lagrangian density of the model exhibit pseudospin-charge separation. In this context, the Hamiltonian associated with the charge degrees of freedom is exactly diagonalized. Further, by means of a perturbative analysis we compute the Lagrangian density, and, at half-filling, we derive the action of the O(4) nonlinear σ-model with a topological Hopf term.

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Borromean window for H_2^+ with screened Coulomb potentials

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Search for Borromean states for few-body quantum systems has gained considerable attention in recent years [1]. For an *N*-body system, a bound state is called Borromean state if there is no path to build it via a series of stable states by adding the constituents one by one. The Borromean binding is intimately related to two other fascinating phenomena, viz. Efimov effects and Thomas collapse. Borromean systems have also appeared in other areas such as nuclear physics, molecular physics, chemical physics and DNA. In this study, we are interested to search Borromean windows for the H_2^+ ions. With abundances of the H_2^+ ions in interstellar matter, and with recent experimental advancements in the experiments of H_2^+ using laser spectroscopy, it is of great important to study various properties of such a three-body system under the influence of screened Coulomb potentials: exp(−μr)/r, where μ is the screening parameters. In this work, we have estimated the critical range of screening parameters to establish Borromean windows for H_2^+ for each partial wave states up to $L = 4$.

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Correlation and relativistic effects for the 4*f* – *nl* and 5*p* – *nl* multipole transitions in Er-like tungsten

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Relativistic and correlation effects are important in calculations of atomic data for low-ionized W ions. Wavelengths, transition rates, and line strengths are calculated for the multipole (E1, M1, E2, M2, and E3) transitions between the excited [Cd]$4f^{13}5p^6nl$, [Cd]$4f^{14}5p^5nl$ configurations and the ground [Cd]$4f^{14}5p^6$ state in Er-like W^{6+} ion ([Cd]=[Kr]$4d^{10}5s^2$). In particular, the relativistic many-body perturbation theory (RMBPT), including the Breit interaction, is used to evaluate energies and transition rates for multipole transitions in this hole-particle system. This method is based on RMBPT that agrees with MCDF calculations in lowest-order, includes all second-order correlation corrections and corrections from negative-energy states. The calculations start from a [Cd]$4d^{14}5p^6$ Dirac-Fock (DF) potential. First-order perturbation theory is used to obtain intermediate-coupling coefficients, and second-order RMBPT is used to determine the multipole matrix elements needed for calculations of other atomic properties [1]. In addition, core multipole polarizability is evaluated in random-phase and DF approximations. These are the first *ab initio* calculations of energies and transition rates in Er-like tungsten. This research was supported by DOE under OFES grant DE-FG02-08ER54951.

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EIT-based all-optical switching and cross-phase modulation under the influence of four-wave mixing

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Photons are superior information carriers and, consequently, manipulation of photon states, such as all-optical switching (AOS) and cross-phase modulation (XPM), has been considered as a promising means in quantum communication and quantum computation. Due to large nonlinear susceptibilities at low-light levels, the AOS and XPM based on the EIT effect make the single-photon operation feasible. However, existence of the four-wave mixing (FWM) process greatly reduces the switching or phase-modulation efficiency and hinders the single-photon operation. Here, we experimentally and theoretically demonstrated that an optimum switching detuning makes the switching efficiency in the EIT-based AOS reach the ideal efficiency even under the influence of FWM [1]. The results of this work can be directly applied to the EIT-based XPM. Our study provides useful knowledge for the research field of low-light-level or single-photon AOS and XPM in FWM-allowed systems.

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Polarization of a focussed beam – Magneto Orbital Dichroism

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We present two experiments involving the interplay between the shape and the polarization of a light beam.

It can be shown [1] that a gaussian focussed beam, asymptotically linearly polarized, acquires through propagation a small circular component, essentially in the Rayleigh range around the focal point. Following [2], we experimentally investigate this effect using Magneto-Circular-Dichroism, *i. e.* differential absorption of the right and left circular components induced by a magnetic field.

We also searched for an analog of MCD using the *orbital* angular momentum of the beam instead of the *intrinsic* angular momentum associated with circular polarization. The effect, if non-zero for the chosen transition around 808.5 nm in Nd:YAG, is at least three orders of magnitude smaller than MCD for $\ell = \pm 1$ Laguerre-Gauss beams.

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Superparabolic level glancing models

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Level crossing models for two-state quantum systems provide an important tool for the study of quantum dynamics in a wide variety of physical problems. The most prominent example of these models, the Landau-Zener model [1], has been successfully applied in many situations over the years. In the recent years, however, there has been a growing interest to study more general dynamics than given by the LZ case [2]. We address and discuss the basic characteristics of the special case of superparabolic level glancing, i.e., when the detuning is proportional to an even power of time and the energy levels reach a degeneracy at a specific point of time but do not actually cross.

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A Raman-Ramsey measurement of the third-order electric polarizability of the cesium ground state using a thermal atomic beam

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The experiment proposed in [1] for an independent measurement of the third order scalar polarizability of the ground state hyperfine structure in Cs, motivated by the 5σ discrepancy between the modern experimental values (Paris[2] with 0.2% precision, and Torino[3] with 2% precision) has produced a result [4], independently verifying the Paris [2] measurement. Details of our experiment, the results, and the limiting systematic effects will be presented.

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Larmor frequency dressing by a non-harmonic transverse magnetic field

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We present a theoretical and experimental study of spin precession in the presence of both a static and an orthogonal oscillating magnetic field, which is non-resonant, not harmonically related to the Larmor precession and of arbitrary strength. Due to the intrinsic non-linearity of the system, previous models that account only for the simple sinusoidal case cannot be applied. We suggest an alternative approach and develop a model that closely agrees with experimental data produced by an optical-pumping atomic magnetometer. We demonstrate that an appropriately designed non-harmonic field makes it possible to extract a linear response to a weak dc transverse field, despite the scalar nature of the magnetometer, which normally causes a much weaker, second-order response.

Effect of pulse shape on excitation line width for coherently driven two-level systems: power narrowing

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We consider the phenomenon of decreasing of the spectral line width with increasing the coupling strength (power narrowing) for the case of two-level system coherently driven by a bell-shaped symmetrical pulse, and a constant detuning. Specifically, we consider couplings with exponentially and power-low falling wings. Picturing the problem in the adiabatic basis, by means of analysis of the adiabatic condition, we show that power narrowing is possible when the asymptotic behavior of the coupling function is given by a power-low [$\sim (t / T)^{-q}$]. The results are of potential application in high-precision spectroscopy.

Electromagnetically induced transparency using evanescent fields in warm atomic vapour

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We investigate EIT in a dense rubidium vapour ($N^{1/3}\lambda > 1$) using selective reflection from a glass-vapour interface near the critical angle for total internal reflection. At incident angles above the critical angle, where the fields are evanescent, we observe a distinctly non-Lorentzian transmission window in the presence of a control field. The window exhibits a sharp cusp whose minimum width was measured to be 1 MHz, which is strong evidence for EIT as the natural line width of the transition is 6 MHz [1]. Furthermore, we investigate the effects of EIT on both the lateral and angular Goos-Hänchen shifts by measuring the position of a Gaussian beam using a balanced detector. A theoretical model describing both the spectrum of the reflected light field and the measured beam shifts is presented and compared to the experimental data. The possibility of light storage and applications to fundamentally compact frequency references [2] and frequency selective beam displacers are discussed.

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Nonlinear magneto-optical effects with cold rubidium atoms

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We present results of our latest experiments on magneto-optical effects in laser-cooled non-degenerate rubidium samples. Interaction of atoms with a linearly polarized light leads to an effective creation of long-lived ground-state Zeeman coherences, which is observed through the nonlinear Faraday effect [1] or free induction decay signals of the Larmor precession. Coherence life-times of up to a few milliseconds are observed in a simple magnetic shield. Application of these effect to the precision magnetometry and its potential limits are presented. Moreover, Zeeman coherences form a versatile tool for studying superposition states which are vital to fundamental atomic physics and quantum information. We demonstrate the dynamics of coherent superposition states under the influence of laser and magnetic fields. Finally, we discuss a new scheme utilizing chirped pulses to virtually instantly create maximum allowed Zeeman coherences [2].

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Quantum optical effects seen in mesoscopic Rydberg atoms

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The direct UV photoexcitation of ground-state potassium atoms to high-lying (n ~ 300) Rydberg states in the presence of weak (< 5mV/cm) rf drive fields at, or near, the Kepler frequency of the final state (~ 230 MHz) is examined. The presence of the drive field leads to the appearance of new features in the excitation spectrum that depend sensitively on the strength and frequency of the field. These features are analyzed with the aid of Floquet theory. Even though very-high-n states are close to the classical limit, evidence of quantum optical effects such as electromagnetically induced transparency and the Autler-Townes splitting can be seen. For weak drive fields the spectra show linear and (small) quadratic energy shifts. With increasing drive field strengths the spectra become more complex as multiphoton transitions become important.

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Laser driven ionization of alkali vapors in an ethane buffer gas by D1 and D2 laser light

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Recently, there has been renewed interest in the dynamics of laser driven ionization of alkali metal vapors in a noble gas/ hydrocarbon buffer gas. Of particular concern is ionization driven by the resonant D1 and D2 light, the environment found in an operating alkali vapor laser[1]. Multistage photo excitation to high lying states is commonly observed and can lead to ionization via direct photo ionization or several collision mechanisms[2]. Our investigation considers two common alkali laser systems where either ^{133}Cs or ^{85}Rb vapors (~10^{13} atoms/cm^3) with 500 Torr of methane, ethane and/or helium buffer gas are the gain media. The alkali systems will be pumped with 0-20W of laser light driving the $n^2S_{1/2} \rightarrow n^2P_{3/2}$ transition at intensities of ~2kW/cm^2, will relax to the $n^2P_{1/2}$ state via buffer gas collisions, and will lase on the $n^2P_{1/2} \rightarrow n^2S_{1/2}$ transition with intensities of ~ 1kW/cm^2. A combination of optical and in situ electrical techniques is used to characterize the system.

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QED theory of the multiphoton cascade transitions in hydrogen and its application to the cosmological hydrogen recombination

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Accurate theory of the multiphoton transitions in hydrogen with cascades is formulated on the basis of QED. As it was discovered in [1], [2] the 2-photon decay of 2*s* level led to the escape of radiation from the matter and allowed for the hydrogen recombination in the early universe. The escaped radiation is observed now as Cosmic Microwave Background (CMB) which properties were measured recently with high accuracy with the cosmic telescopes, providing the knowledge about the hydrogen recombination epoch. Recently it was suggested that the two-photon radiation from the excited $ns(n>2), nd$ levels could give a sizable contribution to the recombination process [3]. Unlike 2*s* case, the decay of the higher excited levels contains the cascade contribution. The description of such decays requires more careful treatment on the basis of QED. We present also a QED theory of the radiation escape for the model of the universe containing only two atoms. This model allows to estimate the role of the two- and three-photon escape from $ns(n>2), nd$ levels compared to the role of 2*s* level. The estimate predicts a correction of 0.2% which has to be taken into account at the recent level of the CMB measurements.

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Coupling matter waves to nano-mechanical oscillators

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We propose a scheme to probe the quantum coherence in the state of a nano-cantilever based on its magnetic coupling (mediated by a magnetic tip) with a spinor Bose Einstein condensate (BEC). By mapping the BEC into a rotor, its coupling with the cantilever results in a gyroscopic motion whose properties depend on the state of the cantilever: the dynamics of one of the components of the rotor angular momentum turns out to be strictly related to the presence of quantum coherence in the state of the cantilever. [1]

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Searching for cosmological spatial variations in values of fundamental constants using laboratory measurements

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The results of a very large study of around 300 quasar absorption systems provide hints that there is a spatial gradient in the variation of the fine structure constant, α [1]. In one direction on the sky α appears to have been smaller in the past, while in the other direction it appears to have been larger. A remarkable result such as this must be independently confirmed by complementary searches. We discuss how terrestrial measurements of time-variation of the fundamental constants in the laboratory, meteorite data, and analysis of the Oklo nuclear reactor can be used to corroborate the spatial variation observed by astronomers [2]. In particular we can expect the yearly variation of α in laboratory measurements to be $\dot{\alpha} / \alpha \sim 10^{-19}\ \mathrm{yr}^{-1}$. The required accuracy is two orders of magnitude below current atomic clock limits, but there are severalproposals that could enable experiments to reach it. These include nuclear clocks and transitions in highly-charged ions that would have very high sensitivity to α-variation.

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A cavity nanoscope

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We present a novel tool for extremely sensitive and spatially resolved absorption spectroscopy on nanoscale objects. To boost sensitivity, multiple interactions of probe light with an object are realized by placing the sample inside an optical scanning microcavity. It is based on a laser machined and mirror-coated end facet of a single mode fiber and a macroscopic plane mirror forming a fully tunable open access Fabry-Perot cavity [1]. Scanning the sample through the microscopic cavity modeyields a spatially resolved map of absorptivity of the sample.

We show first proof-of-principle experiments with single gold nanospheres and nanorods. We demonstrate polarization sensitive absorption measurements as well as measurements on dispersive and birefringent effects of the samples.

Reference

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Control of high harmonic generation by wave front shaping

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The high harmonic generation (HHG) process enables an extension to the short wavelength EUV spectral region and is closely related to generation of attosecond laser pulses. In this process, electrons are first separated from their parent atoms by an intense incident electromagnetic wave, then accelerated in the laser field and can return with a change of the field direction, recombining with the parent atom and emitting energetic photons [1]. We produce HHG in Ar gas with 50fs laser pulses. To control HHG we use a spatial light modulator, shaping the wave front of the fundamental radiation by introducing spatially distributed phase delays. We show that by imposing appropriate phase structures on the fundamental beam the output of high harmonics can be enhanced many fold, and also interference phenomena in HHG can be observed. The extension of the EUV spectrum to shorter wavelength due to enhanced energy release in the electron-ion recombination is also possible. This work was supported by the Welch Foundation (grant No. A1546) and the NSF (grant No. 0722800).

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White-light generation using spatially-structured beams of femtosecond radiation

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We studied white-light generation in water using spatially-structured beams of femtosecond radiation. By changing the transverse spatial phase of an initially Gaussian beam with a 1D spatial light modulator to that of Hermite–Gaussian modes ($HG_{n,m}$), we were able to generate beams exhibiting phase discontinuities and steeper intensity gradients. Under certain experimental conditions, when the spatial phase of an initial Gaussian beam (showing no significant white-light generation) was changed to that of a HG_{01}, or HG_{11} mode, a significant amount of white-light was generated. Because self-focusing is known to play an important role in white-light generation, the self-focusing lengths of the resulting transverse intensity profiles were used to explain this generation. Distributions of the laser intensity for beams having step-wise spatial phase variations were modeled using the Huygens-Fresnel-Kirchhoff integral in the Fresnel approximation and were found to be in excellent agreement with experiment. This work was supported by the Robert A. Welch Foundation (grant No. A1546), the National Science Foundation (grant No. 0722800).

Coherent control multi-dimensional Fourier transform spectroscopy

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We present a method that harnesses coherent control capability to two-dimensional Fourier-transform optical spectroscopy. For this, three ultrashort laser pulses are individually shaped to prepare and control the quantum interference involved in two-photon interexcited-state transitions of a V-type quantum system. In a three-pulse coherent control experiment of atomic rubidium, the phase and amplitude of controlled transition probability is retrieved from a two-dimensional Fourier-transform spectral peak and we show theoretically and experimentally that two-photon coherent control in a V-shape three-level system projects a one-photon coherent transient in a simple two-level system. The second- and third-order spectral phase terms of a shaped laser pulse play the roles of time and quadratic spectral phase, respectively, in conventional coherent transients [1, 2].

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Precision attosecond physics with atomic hydrogen

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We have performed the first investigations of the ionisation dynamics of atomic hydrogen (H) by strong-field few-cycle laser pulses. We demonstrate quantitative agreement between *ab initio* theory and experiment at the 10% level over an unprecedented range of laser intensity and electron energy [1] and use the results to perform laser intensity calibration with 1% accuracy. We present initial measurements of carrier-envelope phase (CEP) dependence of the H photoelectron yield, which will enable accurate *ab initio* calibration of absolute laser CEP.

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Monte Carlo simulations of an unconventional phase transition for a 2d dimerized quantum Heisenberg model

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Motivated by the indication of a new critical theory for the spin-1/2 Heisenberg model with a spatially staggered anisotropy on the square lattice, we re-investigate the phase transition of this model induced by dimerization using first principle Monte Carlo simulations. We focus on studying the finite-size scaling of $\rho_{s1}2L$ and $\rho_{s2}2L$, where L stands for the spatial box size used in the simulations and ρ_{si} with $i \in \{1, 2\}$ is the spin-stiffness in the i-direction. Remarkably, while we observe a large correction to scaling for the observable $\rho_{s1}2L$, the data for $\rho_{s2}2L$ exhibit a good scaling behavior without any indication of a large correction. As a consequence, we are able to obtain a numerical value for the critical exponent ν which is consistent with the known $O(3)$ result with moderate computational effort. Specifically, by fitting the data points of $\rho_{s2}2L$ to their expected scaling form, we obtain $\nu = 0.7120(16)$ which agrees quantitatively with the most accurate known Monte Carlo $O(3)$ result $\nu = 0.7112(5)$.

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Active control of magnetic field and gradient in ultracold experiments

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Work has been carried out to design a magnetic field and gradient compensation system for ultracold strontium experiment. A total of eight magnetic sensors (with 3-axis measurements) are arranged in a cuboid configuration around the atomic cloud. An active compensation system is being designed, with the measurement outcomes feedback electronically to adjust the current flowing through the compensation coils. Both the unwanted A.C. and D.C. components of the magnetic field and gradients, $\frac{\partial B_x}{\partial x}$, $\frac{\partial B_y}{\partial y}$ and $\frac{\partial B_z}{\partial z}$, can then be compensated. Additional information on the curvature of the magnetic field can be deduced from the measurements to give a more detailed information of the magnetic field around the atomic cloud. This system should enable the control of magnetic field below the level of 0.1 mG for for the ultracold strontium experiment.

Random laser in cold atoms

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Random lasing in a medium with scattering and gain has been predicted by V. Letokhov [1] with threshold is given by a critical size of the medium required to overcome losses via scatetring through the surface. Such random lasing has is also under investigation in astrophysical systems [2], where non thermal equilibrium coniditions can exist in dilute cloud of plasma. Many random lasers based on condensed matter systems have been realized in the last 25 years, but the existence of gaz lasers, the realization of random lasing in dilute atomic vapours has not been reported. We show that a cloud of cold atoms can be a good tool to study random laser with resonance scattering feedback [3]. Using two photon hyperfine Raman gain with the incident laser tuned to an atomic line provinding enhanced scattering for the anti-stockes photon, gain and scattering have been combined with a single atomic species of ^{85}Rb. We observe signatures of random lasing in the total emission which displays a threshold behaviour with optical thickness of the cloud.

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Information-theoretic properties of Rydberg atoms

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The internal disorder of Rydberg atoms as contained in their position and momentum probability densities is examined by means of the following spreading and information-theoretic quantities: the radial and logarithmic expectation values, the Shannon entropy and the Fisher information. The leading term of these quantities is rigorously calculated by use of the asymptotic properties of the concomitant entropic functionals of the Laguerre and Gegenbauer orthogonal polynomials which control the wavefunctions of the Rydberg states in both position and momentum spaces. The associated generalized Heisenberg-like, logarithmic and entropic uncertainty relations are also given. Finally, application to the experimentally accesible linear ($l = 0$), circular ($l = n - 1$) and quasicircular ($l = n - 2$) states is explicitly done.

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Fault of interferometer passbands equidistance with its length variation

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It is well known, when a plane electromagnetic wave passing through an interferometer (for example Fabry-Perot or Michelson) its transmission bands are equidistant with an interval equal to radiation half wavelength. This has been the basis for creating the optical ruler, in which stabilized laser wavelength serves as the reference length [1]. The femtosecond laser [2] can be used for creation of the length standard too. In the present study it was found that the shape of the interferometer passbands is asymmetric due to laser beam divergence. Physics of this phenomenon is caused by the difference between wavefront curvatures of interfering light beams. It is shown that the asymmetry of the bands depends on the different factors: interferometer length, mirror displacement relative to the beam waist, the beam orificing at the photodetector, misalignment of the interferometer mirrors, mirror transmission.

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Enabling technologies for integrated atom chips

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Atomic physics experiments based on ultracold atoms have a wide range of applications beyond the laboratory as time and metrological standards, inertial guidance sensors, gravitational field sensors, magnetometers, and they are likely to play a crucial part in emerging quantum based technologies such as cryptography, quantum simulators, networks and information processing. Over a decade of research has been devoted to translating these experiments onto microfabricated platforms known as atom chips. These are, however, far from ‘lab-on-a-chip’ and remain firmly ‘chip-in-a-lab’ devices. This is due to the need for a vast infrastructure of UHV systems, atom sources, laser systems and detectors, which have yet to be completely miniaturized. Our research is directed at tackling this problem by identifying and adapting materials and methods from the planar micro/nanofabrication industry to perform the roles of standard atomic physics apparatus in an integrated and mass-manufacturable way. Our initial studies into obtaining, maintaining and measuring ultrahigh vacuum in a micro-litre cavity are presented as well as integrated atom sources and novel magneto-optical trap geometries.