Invited talks

From Optical Pumping to Quantum Gases

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A full control of internal and external degrees of freedom of atoms and of their interactions can now be achieved in atomic physics experiments. These achievements have been made possible by the development of optical pumping methods first proposed sixty years ago, by the availability of laser sources first realized fifty years ago, and by the invention of new methods, like laser cooling and trapping, evaporative cooling and Feshbach resonances. We will review in this paper a few breakthroughs in the recent evolution of atomic physics, showing the continuity between researches done at different times and emphasizing the new fruitful dialogue which is being established between atomic physics and other disciplines like theoretical physics, condensed matter physics and few body physics. The possibility to achieve ultracold gaseous samples of strongly interacting atoms and to control all experimental parameters allows one to explore new physical situations, to realize simple models of more complex quantum systems found in other fields of physics and to get a better understanding of their behavior.

Synthetic Electric and Magnetic Fields for Ultracold Neutral Atoms

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Ultracold neutral atoms and quantum degenerate neutral atomic gases have proved to be useful in the simulation of the quantum behavior of a number of models, Hamiltonians, and physical systems. One reason for this is the ability to control the Hamiltonian for the atoms in ways that are difficult in other systems; another is the ability to measure certain quantities, like momentum distributions, that are often not easily measured in other systems. Bose condensation, Fermi degeneracy, Cooper pairing, BCS/BEC crossover, and the behavior of quantum particles in periodic potentials are among the areas where cold atoms exhibit behavior that is hard to observe in analogous condensed matter systems. One of the difficulties facing the simulation of interesting Hamiltonians with neutral atoms is in simulating the response of charged particles to external electromagnetic fields, particularly to magnetic fields. One approach has been to use rotation, where the Coriolis force mimics the Lorentz force. Because of some limitations of this approach, such as the introduction of a centrifugal force, and various technical imperfections, other techniques have been proposed involving the simulation of a magnetic vector potential. The idea behind such an approach is that the Hamiltonian for a charged particle in a magnetic vector potential can be written as $H = (\mathbf{p} - q\mathbf{A})^2/2m$, where $\mathbf{p}$ is the particle's canonical momentum (the quantity canonically conjugate to position), q is its charge, m is its mass, and $\mathbf{A}$ is the vector potential. Evidently, the introduction of a vector potential is equivalent to displacing the origin of the particle's energy-momentum dispersion curve from having its minimum at $\mathbf{p} = 0$.

Using a Bose-Einstein condensate of ^{87}Rb atoms we produce an effective vector potential by coupling together different magnetic sublevels in the $F = 1$ electronic ground state, using Raman transitions that also transfer linear momentum to the atoms. By adjusting the strength and Raman detuning of the coupling, we can shift the position of the minimum of the atoms' dispersion curve, thus creating a non-zero, uniform, effective vector potential (for a specific choice of gauge). Applying a gradient magnetic field that shifts the magnetic sublevels in a space-dependent manner produces a curl of the effective vector potential and hence a synthetic magnetic field. This synthetic magnetic field creates vortices in the Rb cloud, just as if the cloud had been rotating. We have also completed the analog with a true magnetic vector potential by showing that a time-varying effective vector potential creates a synthetic electric field. We measure the effect of this synthetic E-field on both the canonical and mechanical atomic momentum.

We hope to use the synthetic field approach to simulate Quantum Hall and Fractional Quantum Hall effects in our neutral bosonic system.

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Artificial gauge potentials for neutral atoms: from Sagnac's to Berry's phase

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The simulation of condensed matter systems is certainly one of the most appealing perspectives opened by the recent developments in the physics of cold atomic gases[1]. Among the large variety of quantum collective phenomena that one hopes to address with atomic vapours, magnetism is certainly one of the richest. However the quest for the simulation of magnetism immediately raises a challenging question: how can a system of neutral atoms behave as an assembly of charged particles in a magnetic field?

The talk will review some promising approaches to answer this question both in a bulk system[2] and in an optical lattice[3]. A first already well explored path is to rotate the gas and to take advantage of the similarity between the Lorentz force acting on electrons in a magnetic field, and the Coriolis force in a rotating frame (or its quantum equivalent, i.e. the Sagnac phase) [4,5]. A second possibility is based on the Berry's phase that an atom accumulates when it follows adiabatically one of its internal levels during its motion in a well chosen energy landscape[6,7]. In this case, the Berry's phase appears as a substitute for the Aharonov-Bohm phase of a charged particle in a magnetic field. Other interesting strategies use a transient regime to reach a targeted many-body correlated state[8,9]. In all cases the goal is to produce atomic states that would be analogous of those characteristic of fractional quantum Hall physics, with a wealth of exotic properties such as anyonic statistics and non Abelian dynamics.

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Quantum Gas Microscope - Probing the Superfluid to Mott Insulator Transition at the Single Atom Level

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The Quantum Gas Microscope[1] enables high fidelity detection of single atoms in a Hubbard-regime optical lattice, bringing ultracold atom research to a new, microscopic level. We investigate the Bose-Hubbard model using space- and time-resolved characterization of the number statistics across the superfluid - Mott insulator quantum phase transition.[2] Site-resolved probing of fluctuations provides us with a sensitive local thermometer, allows us to identify microscopic heterostructures of low entropy Mott domains, and enables us to measure local quantum dynamics, revealing surprisingly fast transition timescales. Our results may serve as a benchmark for theoretical studies of quantum dynamics, and open new possibilities for realizing and probing quantum magnetism.

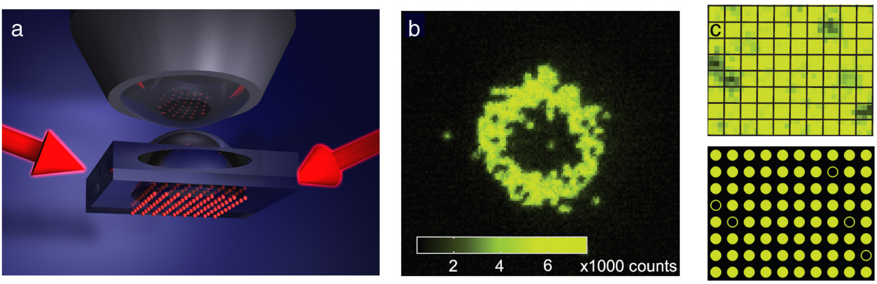

Figure 1: *Mott insulator (MI) in a Quantum Gas Microscope. (a) Sketch of Quantum Gas Microscope, enabling high fidelity single lattice site imaging. (b) Mott insulator shell structure with $n = 1$ MI (bright ring), surrounding a $n = 2$ MI core (dark). (c) near perfect n=1 Mott insulator.*

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Topological Excitations in Ultracold Atomic Gases

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Gaseous Bose-Einstein condensates with spin degrees of freedom host a wealth of topological excitations. This is because the system involves different types of interactions such as the Hartree, spin-exchange, and dipole-dipole interactions that have different symmetries and varied energy scales over several orders of magnitudes. Consequently, the full $U(1) \times SO(3)$ symmetry is spontaneously broken in each phase, producing a rich variety of order-parameter manifolds. Depending on the symmetry of the order parameter, different phases feature different topological excitations such as integer, fractional, Abelian, and non-Abelian vortices; Dirac and t'Hooft-Polyakov monopoles; Mermin-Ho, Anderson-Toulouse, Shankar, and knot skyrmions. Remarkably, all of those exotic excitations can be realized experimentally. In the talk, I will review which topological excitations can be realized in which phase, and discuss their applications to studies such as quantum turbulence and the Kibble-Zurek mechanism.

This work was done in collaboration with Y. Kawaguchi, M. Kobayashi, M. Nitta, and H. Saito.

Non-Abelian Josephson effect

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We investigate the non-Abelian Josephson effect in $F = 2$ spinor Bose-Einstein condensates with double optical traps. We propose a real physical system which contains non-Abelian Josephson effect and has very different density and spin tunneling characteristics compared with the Abelian case. We calculate the frequencies of the pseudo Goldstone modes in different phases between two traps, respectively, which are the crucial features of the non-Abelian Josephson effect. We also give an experimental protocol to observe this novel effect in future experiments[1]. We describe an optical system that allows for direct observation of the photonic Josephson effects in two weakly linked microcavities containing ultracold two-level atoms. We show that, by moving the ultracold atoms within one cavity, we could simulate an analogous superconducting circuit and realize both the alternating- and direct-current (ac and dc) photonic Josephson effects. This provides a strategy for constructing novel interference devices of coherent photons and enables new investigations of the effect of many-body physics in strongly coupled atom-cavity systems[2].

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Emergence and study of turbulence in a Bose condensate

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In this work we review our technique to generate turbulence in a BEC, where an oscillating field superimposed to the trapping field creates displacement, rotation and deformation of the trap potential, promoting the generation of vortices[1,2]. The generation of quantized vortices is investigated as a function of the amplitude of oscillation as well as time of excitation. The results allow the construction of a diagram for stable structures, which can be justified based on numerical calculations using the Gross-Pitaevskii equation. For severe oscillatory excitation, we have observed a fragmentation of the quantum atomic fluid, which will be discussed in this presentation. Hydrodynamic considerations allow us to understand the occurrence of an anomalous expansion behavior for the cloud, when under turbulent regime. Finally we apply the concepts of generalized thermodynamic variables to understand the variation of pressure during the occurrence of turbulence in the condensate. The concept of flow and Reynolds numbers is applied to the oscillations revealing values associated with the turbulent regime. *(Work done in collaboration with the following students and PD: E. Henn, J. Seman, P. Castilho, K. Magalhaes, R. Shiozaki, E. Ramos, M. Caracanhas, C. Castelo-Branco, P. Tavares , F. Poveda, G. Telles, G. Bagnato and the participation of external collaborators: G. Roati, A. Fetter, V. Yukalov , V. Romero-Rochin and M. Tsubota).* Financial support from FAPESP and CNPq-Brazilian agencies.

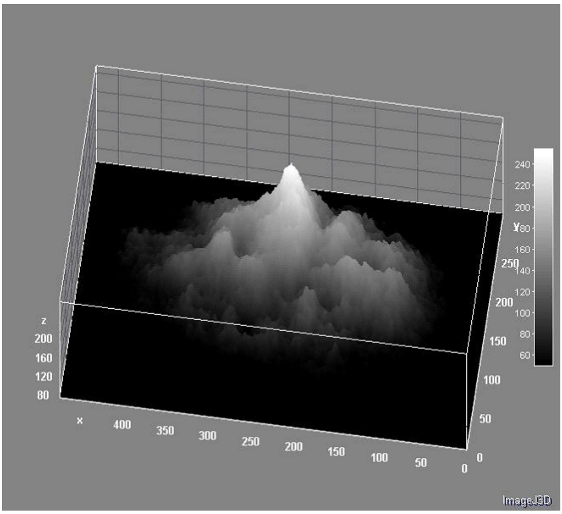

Figure 1: *Density distribution for a turbulent cloud.*

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A trapped single ion inside a Bose-Einstein condensate

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In recent years, ultracold atoms have emerged as an exceptionally well controllable experimental system to investigate fundamental physics, ranging from quantum information science to simulations of condensed matter models. Here we go one step further and explore how cold atoms can be combined with other quantum systems to create new quantum hybrids with tailored properties. Coupling atomic quantum many-body states to an independently controllable single-particle quantum system gives access to a wealth of novel physics and to completely new detection and manipulation techniques. In the talk, we will report on recent experiments in which we have for the first time deterministically placed a single ion into an atomic Bose Einstein condensate[1]. A trapped ion, which currently constitutes the most pristine single particle quantum system, can be steered with nanometer precision within the atomic cloud and can be observed and manipulated at the single particle level. In the created single-particle/many-body composite quantum system we show sympathetic cooling of the ion and observe chemical reactions of single particles in situ[2]. An outlook into possible future developments will be given.

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Helium fine structure theory for the determination of α

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The calculation of energy levels of atomic and molecular systems has reached such a precision level, which make possible accurate tests of Quantum Electrodynamics, the determination of fundamental constants and sets the accurate bounds for non-electromagnetic interactions between electrons and nuclei. The computational approach which allows for systematic inclusion of all corrections and estimation of uncertainty is based on the expansion of energy levels in powers of the fine structure constant α. Small effects coming from the finite nuclear mass, its size and even the exchange of Z_0 boson can all be included perturbatively. As an example the most accurate determination of nuclear charge radii for light atoms such as: H, D, He, Li, and Be atoms comes not from the traditional electron-nucleus scattering experiments, but from the atomic spectroscopy measurements supplemented with the modern atomic theory.

When nuclear finite size is well known or does not contribute to the energy splitting, the fundamental physical constants such as: electron mass or the fine structure constant α can be determined. As it was noticed by Schwartz[1] in 1964, the helium fine splitting of $2P_J$ levels is a very good candidate for the determination of α. It took almost 50 years of theoretical studies to complete the calculations, reaching about 31 ppb accuracy in the fine structure constant, slightly less than that from the electron $g-2$ and atomic recoil measurements. These determinations of α by different methods provide a sensitive test of consistency of theory across a range of energy scales and physical phenomena.

We will report a rigorous QED calculation [2] [3] of the fine-structure intervals $\nu_{01} = 2^3P_0 - 2^3P_1$ and $\nu_{02} = 2^3P_0 - 2^3P_2$ for helium-like ions with $Z = 2\dots10$. The calculational approach is based on an expansion of both relativistic and QED effects in powers of the fine-structure constant α. This expansion allows one to consistently improve the accuracy of calculations[4] by accounting for various effects order by order, and is now complete up to orders $m\alpha^7$ and $m^2\alpha^6/M$. Currently the main source of theoretical uncertainty is the unknown $m\,\alpha^8$ correction, and its estimation from the combined experimental and theoretical studies will be proposed.

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Perspectives for precision tests with antihydrogen

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After a first generation of experiments[1,2] has demonstrated the feasibility of forming in a controlled manner low-energy antihydrogen atoms via a series of different techniques, a second generation of experiments is now attempting to either trap these cold atoms[3,4], or to produce an atomic beam of antihydrogen atoms[5,6].

The goal of these experiments is to carry out comparative precision spectroscopy between Hydrogen and Antihydrogen, in view of testing the CPT theorem, either through 1S-2S spectroscopy, or via a measurement of the hyperfine splitting of the ground state of antihydrogen. A related class of experiments combines techniques from these experiments with techniques from spectroscopic studies of Positronium to test the gravitational interaction between matter and antimatter.

An overview of the challenges, limitations and perspectives of these, and results from related experiments will be presented, and an outlook for the next several years will be given.

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Precision measurement of the n=2 triplet P states of helium and the determination of the fine-structure constant

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The J=1 to J=2 fine-structure interval of n=2 triplet P atomic helium has been measured[1] to a precision of 350 Hz using the Ramsey method of separated oscillatory fields. A beam of metastable (n=2 triplet S) helium atoms is created from an electric discharge, and these are excited up to the n=2 triplet P states with a 1083-nm diode laser. The fine-structure transition is driven with microwave fields. The Ramsey method of separated oscillatory fields allows for narrowing the resonance to subnatural linewidths. It also allows for repeating the measurement with a wide variety of lineshapes, which allows for direct tests of many of the systematic effects.

At an uncertainty of 350 Hz, this measurement is the most precise in a long series[2] of measurements of the 2^3P fine-structure since Schwartz suggested[3] in 1964 that a comparison of precise theory and precise experimental measurement of the helium fine structure could lead to a precise determination of the fine-structure constant. Theory has also advanced[4] over the past decade, and most recently a calculation[5] complete to order $\alpha^5 Ry$ has been published.

We are beginning even more precise measurements of this J=1 to J=2 interval, with the hope of measuring it to a precision of 60 Hz. Following that measurement, we intend to measure the larger J=0 to J=1 interval to the same 60 Hz level of precision. A combination of these more precise measurements and precise theory could be used to determine the fine-structure constant to a precision of one part per billion.

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Nuclear clock and variation of fundamental constants

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I present a review of recent works devoted to the variation of the fine structure constant alpha, strong interaction and fundamental masses.

There are new results for the variation based on the quasar absorption spectra data. These results may be used to predict the variation effects for atomic clocks.

I also describe recent theoretical and experimental works on the nuclear clock based on the narrow UV (7 eV) transition between the ground and first excited states in 229Th nucleus. The effect of the fundamental constant variation in this transtion may exceed the effects in atoms by several orders of magnitude.

Theories unifying gravity with other interactions suggest temporal and spatial variation of the fundamental ”constants” in expanding Universe. The spatial variation can explain fine tuning of the fundamental constants which allows humans (and any life) to appear. We appeared in the area of the Universe where the values of the fundamental constants are consistent with our existence.

Space Clocks and Fundamental Tests

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We will first review the recent progress in atomic clocks operating in the microwave and optical domain of the electromagnetic spectrum. The second of the SI system of units is realized today with an accuracy of $3\,10^{-16}$ by a number of laser cooled atomic fountains worldwide. Optical clocks have recently reached a frequency stability and accuracy in the 10^{-18} range[1], opening new perspectives for time keeping and fundamental tests.

We will then present the status of the ACES mission[2] of the European Space Agency scheduled for flight to the International Space Station from 2013 to 2015. ACES will embark a laser cooled cesium clock designed for microgravity operation (PHARAO), an active hydrogen maser (SHM), and a high precision time transfer system operating in the microwave domain. This microwave link (MWL) will enable frequency comparisons between the space clocks and a network of ground based clocks belonging to worldwide metrology institutes and universities. The link is designed for obtaining a relative frequency resolution of 10^{-17} after a few days of measurement duration for intercontinental comparisons. In 2009-2010, all elements of the flight payload have successfully passed the Engineering Model tests and flight models are under construction. We will present the latest measurement results and flight model designs.

In a second part we will describe tests of fundamental physical laws using ultra-stable clocks in space and on the ground that are planned for the ACES mission. An improved measurement of Einstein's gravitational red-shift will be made at the two parts per million level. By comparing clocks of different nature at the 10^{-17} /year level new limits will be obtained for the time variation of the fundamental constants of physics such as the fine structure constant alpha and the ratio of electron to proton mass. The ability to compare microwave and optical clocks using the recently developed frequency comb technique opens a wide range of possibilities in clock comparisons. Finally a new kind of relativistic geodesy based on the Einstein effect will provide information on the Earth geoid, complementing the recent determination obtained by space geodesy methods.

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Optical lattice clocks and frequency comparison

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To date, optical clocks based on singly trapped ions[1] and ultracold neutral atoms trapped in the Stark-shift-free optical lattices[2] are regarded as promising candidates for future atomic clocks. Since 2006, Sr-based "optical lattice clocks" have been evaluated close to the Cs clocks' uncertainty limit internationally[3]. To further reduce their uncertainty and instability, there remain essential experimental challenges. One is to find out better lattice geometries as well as interrogated atom species that bring out the potential performance of the clock scheme, taking into account the collisional frequency shift, the black body radiation shift, and the atomic multipolar and hyperpolarizability effects. The other is to fully utilize the advantage of number N of atoms to improve the clock stability, which is hampered by the instability of a probe laser of typically 5×10^{-16} at 1 s that is due to the thermal noise of a reference cavity[4].

In this talk, we first discuss optimal designs of optical lattice clocks in view of the quantum statistics, relevant atomic spins, and multipolar interactions of atoms with lattice laser fields. This leads to two favorable configurations for the clock: One-dimensional (1D) optical lattice loaded with spin-polarized fermions and 3D optical lattice loaded with bosons[5]. We present frequency comparison of these two optical lattice clocks using fermionic ^{87}Sr and bosonic ^{88}Sr, which offers an important step to ascertain the optical lattice clocks' uncertainty beyond 1×10^{-16}. In particular, we refer to the "atomic motion insensitive" wavelength that provides the precise definition[6] of the "magic wavelength" including atomic multipolar interactions.

We then mention our ongoing approaches to pursue the quantum projection noise limit of optical lattice clocks. Synchronous interrogations of two optical lattice clocks by the same probe laser allow canceling out its frequency noise as a common mode noise in the evaluation of their relative stability; therefore the scheme enables us to explore intrinsic stability of the clock less affected by the probe laser stability. On the other hand, in order to overcome the clock instability that is predominantly determined by the "thermal noise limit" of a probe laser, we propose a novel frequency stabilization scheme for optical lattice clocks that does not employ "electron shelving" technique for the clock state detection. We will discuss possible impacts of these approaches.

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Single-atom optical clocks - it's about time!

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Atom lasers and their prospects for application to precision inertial measurements

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Atoms in free fall have proved to be very sensitive probes of inertial quantities such as gravity, gravity gradients, acceleration, and rotation. The ideal source for such an experiment would have a narrow transverse momentum width, would be high flux, bright and squeezed and would be used in conjunction with large momentum transfer beam splitters and high quantum efficiency detection operating below the projection noise limit. Although the atom laser appears to be a promising source for such applications, there are substantial hurdles that must be overcome. I will discuss the building blocks we have put in place to develop the atom laser to be a useful tool for precision inertial measurement.

We have investigated the spatial mode of atom lasers both theoretically and experimentally. Although the classical properties of an atom laser like the spatial mode do not, in principle, affect the signal to noise ratio in an interferometric measurement, in practice they often do and optimising classical properties like the spatial mode is probably important if these sources are to be applied to precision measurement[1].

At fixed flux, pulsed sources have substantially higher density than continuous sources leading to higher mean field effects. For this reason, a continuous atom laser is very desirable. We have investigated a spontaneous emission based pumping scheme and have demonstrated simultaneous pumping of the condensate and extraction of an atom laser beam. This is a necessary first step in producing a continuous atom laser[2].

Squeezing in quantum optics is achieved via evolution of the laser field in a non-linear medium. Control of the non-linearity in an atom laser beam is likely to be similarly important if we are to produce freely propagating squeezed states. In preparation for this work, we have Bose condensed ^{85}Rb[3].

In recent work, we have investigated projection noise limited atom interferometry using an atom laser as a source. We have developed sub-projection noise limited absorption imaging and have characterised the contributions of photon shot noise and atom projection noise in our detection system. This work is the precursor to atom laser interferomtery at sensitivities exceeding the projection noise limit using freely propagating atom laser beams[4,5].

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A Precision Measurement of the Gravitational Redshift and other Applications of Atom Interferometers

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A central prediction of metric theories of gravity, such as General Relativity, is that lowering the gravitational potential at which a clock resides by ΔU will slow it down by a factor of $1 + \Delta U/c^2$, where c is the velocity of light.[1] This gravitational redshift is important to the global positioning system, timekeeping, or experiments with space-based clocks. It has been confirmed for clocks on a tower, an aircraft, and a rocket,[2] to an accuracy of up to 7×10^{-5}.

In an atom interferometer,[3] an atomic matter wave originally in free fall is split so that it takes two paths having different elevations (Fig. 1, left). When the waves interfere, the probability of detecting the atom is given by ϕ, the phase difference accumulated by the waves. The central realization of this work is that $\phi = \phi_r + \phi_t + \phi_i$ can be interpreted as the gravitational redshift $\phi_r = \omega_C \int (1 + \Delta U/c^2) dt$ to the Compton frequency $\omega_C = mc^2/\hbar \simeq 2\pi \times 3 \times 10^{25}$ Hz of the matter waves, where m is the atom's mass and $\hbar$ the reduced Planck constant; two other contributions, due to the time dilation (ϕ_t) and the laser-atom interaction (ϕ_i), cancel. The experiment confirms the predicted gravitational redshift to an accuracy of 7×10^{-9}.

A similar interpretation can be applied to many atomic physics phenomena, such as Bloch oscillations,[4] confirming the gravitational redshift to lower accuracy but for sub-micron distance scales (Fig. 1, right).

Ideas for future applications of atom interferometers, such as detection of gravitational waves, will be presented.

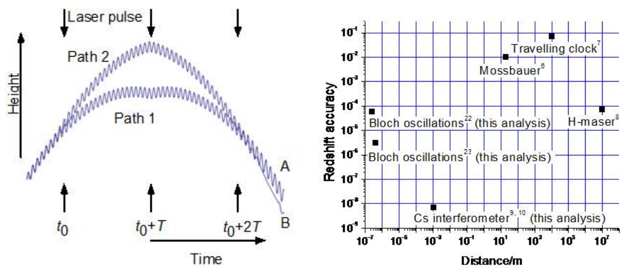

Figure 1: *Left: Atom interferometer. Right: Results of various redshift tests compared by accuracy and relative elevation.*

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The charge radius of the proton

Randolf Pohl, A. Antognini, F. Nez, F.D. Amaro, F. Biraben, J.M.R. Cardoso, D.S. Covita, A. Dax, S. Dhawan, L.M.P. Fernandes, A. Giesen, T. Graf, T.W. Hänsch, P. Indelicato, L. Julien, C.-Y. Kao, P. Knowles, J.A.M. Lopes, E.-O. Le Bigot, Y.-W. Liu, L. Ludhova, C.M.B. Monteiro, F. Mulhauser, T. Nebel, P. Rabinowitz, J.M.F. dos Santos, L.A. Schaller, K. Schuhmann, C. Schwob, D. Taqqu, J.F.C.A. Veloso, F. Kottmann

The CREMA collaboration

The charge radius r_p of the proton, the simplest nucleus, has so far been known only with a surprisingly low precision of about 1%, using mainly hydrogen spectroscopy data and bound-state QED calculations. An independent value from electron-proton scattering is even less accurate (2%), and limits the test of bound-state QED in hydrogen.

We have recently measured the Lamb shift in muonic hydrogen (μp, i.e. a proton orbited by a negative muon) with 14 ppm precision via laser spectroscopy of the $2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$ transition. The Lamb shift in μp is dominated by vacuum polarisation, and the finite size effect is as large as 2% of the total Lamb shift. Therefore, we have been able to determine the proton rms charge radius to 10^{-3}. This new limit is imposed by the theory (mainly the proton polarizability term) - the experimental data could provide a twice better uncertainty on r_p.

The new value of r_p is 10 times more precise than the previous one, but it deviates by 5σ from the present CODATA value, and $3\,\sigma$ from the value obtained by electron-proton scattering. The origin of this uncertainty is yet unknown. If it comes from QED calculations in μp, a term as large as 1.5×10^{-3} of the total Lamb shift must be missing which seems astonishingly large. Alternatively, the problem could come from hydrogen spectroscopy or from the calculation of the Lamb shift in hydrogen. If theory in μp is correct, a new value for the Rydberg constant R_∞ is obtained which differs from the present CODATA value by $5\,\sigma$. The Rydberg constant deduced using our r_p is five times more precise than the present CODATA value.

We have also recorded a second resonance line in muonic hydrogen. The data is still being analyzed, but a preliminary analysis confirms the value of r_p deduced by the first resonance in μp. From this second resonance we will deduce the 2S hyperfine splitting in μp. We will be able to determine the Zemach radius (radius of the magnetic moment distribution) of the proton with a few per cent accuracy.

In addition, we have observed three resonances in muonic deuterium. When analyzed, we will be able to give a deuteron charge radius and/or the deuteron polarizability, complementing isotope shift measurements in ordinary hydrogen and deuterium.

Integrated Quantum Photonics

D Bonneau, P Kalasuwan, A Laing, T Lawson, JCF Matthews, A Peruzzo, K Poulios, P Shadbolt, P Jiang, M Lobino, A Politi, M Rodas Verde, X-Q Zhou, MG Thompson, JL O'Brien[1]

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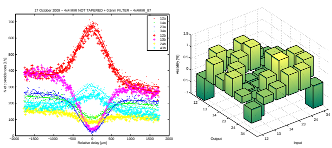
Of the various approaches to quantum computing [1], photons are particularly appealing for their low-noise properties and ease of manipulation at the single qubit level [2]. Encoding quantum information in photons is also an appealing approach to quantum communication, metrology [3], measurement [4] and other quantum technologies [5]. However, the implementation of optical quantum circuits with bulk optics is reaching practical limits. We have developed an integrated waveguide approach to photonic quantum circuits for high performance, miniaturization and scalability [6]. We demonstrate high-fidelity silica-on-silicon integrated optical realizations of key quantum photonic circuits, including two-photon quantum interference and a controlled-NOT logic gate. We have demonstrated controlled manipulation of up to four photons on-chip, including high-fidelity single qubit operations, using a lithographically patterned resistive phase shifter [7]. We have used this architecture to implement a small-scale compiled version of Shors quantum factoring algorithm [8] and combined it with superconducting single photon detectors [9]. We have also demonstrated how quantum process discrimination can be implemented with photonic circuits [10]. Finally, we describe our most recent results, including quantum interference in multi-mode interference devices (Fig. 1), quantum walks of correlated particles, and an improved implementation of quantum logic circuits that harnesses higher dimensional Hilbert space.



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Strongly interacting Fermi gases: from ultracold atoms to molecules

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I will make a brief overview of the studies of strongly interacting atomic Fermi gases and focus on new physics that one expects in upcoming experiments with degenerate mixtures of different fermionic atoms. The new expected physics is mostly related to the difference in masses of atomic constituents. This difference manifests itself in collisional properties of heteronuclear Feshbach molecules formed on the positive side of the resonance (atom-atom scattering length $a > 0$): for a sufficiently large mass difference inelastic collisions should reflect the presence of 3-body Efimov bound states. Another issue is the character and width of the strongly interacting regime, which for a large mass difference should be much wider than in the case of the same atoms in different hyperfine states. Special attention will be paid to the *p*-wave resonance for atomic fermions where inelastic collisions strongly limit the lifetime of the gas in the strongly interacting and molecular regimes. I then turn to ultracold fermionic polar molecules, which have been recently obtained in the ground state in JILA and Heidelberg experiments. At JILA the KRb molecules have been cooled almost to the regime of quantum degeneracy (200 nK at densities of the order of 10^{13} cm^{-3}), which opens fascinating prospects to create novel macroscopic quantum states. The key issue here is the long-range anisotropic dipole-dipole interaction between polar molecules aligned by an electric field. I will first discuss possibilities to obtain *p*-wave superfluids, in particular the $p_x + ip_y$ state promising for topologically protected quantum information processing. Second, I will describe a novel BCS-BEC crossover that can emerge in bilayered systems of polar molecules oriented perpendicularly to the plane of the layers. This system should be collisionally stable and undergo superfluid pairing in which Cooper pairs are formed by fermionic molecules of different layers and transform to real bound states (sort of molecules) under an increase of the density or decrease in the interlayer spacing.

Thermodynamics of an ultra-cold Fermi gas

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Ultra-cold Fermi gases constitute benchmark experimental systems for the understanding of many-body quantum phenomena. Recently, we have implemented a new measurement scheme probing directly the equation of state of such systems. We will show how it allowed us to map the full parameter space by tuning temperature[1], spin imbalance and interaction strength[2]. Our measurements suggest a Fermi liquid behavior of the normal phase that we investigated theoretically from the properties of an impurity immersed in a Fermi sea[3].

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Universal structure of a strongly interacting Fermi gas

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Universality is a remarkable property of strongly interacting systems of fermions. For sufficiently strong interactions, all dilute Fermi systems behave identically on a scale given by the average particle separation. With the discovery of universality in the Bose-Einstein condensate to Bardeen-Cooper-Schrieffer superfluid crossover, ultracold Fermi gases near Feshbach resonances have become a central topic in atomic physics.

We show and experimentally verify a new exact property of universal Fermi gases. The static structure factor $S(q)$, given by the Fourier transform of the density-density correlation function, displays a universal scaling proportional to the inverse of the momentum $(1/q)$ at short-range (high q). We derive this result from Tan's relations[1] - a set of exact results linking bulk thermodynamic properties to a single short-range coefficient known as the contact $\mathcal{I}$. Our prediction is experimentally verified using Bragg scattering of ultracold ^{6}Li atoms from a periodic optical potential[2], providing a new measure of Tan's contact and confirmation of this universal relation[3]. We apply the f-sum rule to normalise our measured Bragg spectra which greatly improves the accuracy of the structure factor measurement. We also use Bragg spectroscopy to measure the temperature dependence of the contact at unitarity, over the temperature range $0.1 \rightarrow 1.0\, T_F$. At high temperatures our results are compared to calculations based on the virial expansion[4].

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Dipolar Effects in Ultracold Molecules*

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Recently, there has been important progress in the investigation of ultracold polar molecules in the absolute ground state, thus opening intriguing perspectives for strongly correlated quantum systems under the influence of long-range dipolar forces.[1,2] In my talk I will give a general overview of recent achievements in the field and present latest results of our experiments.

We have studied the formation of LiCs molecules via photoassociation (PA) in a double-species magneto-optical trap. The LiCs dimer is a particularly promising candidate for observing dipolar effects, as it possesses the largest dipole moment of all alkali dimers (5.5 Debye in the ground state[3]). Ultracold LiCs molecules in the absolute rovibrational ground state $X^1\Sigma^+$(v=0, J=0) were formed by a single photo-association step. The rotational and vibrational states of the ground state molecules were determined in a setup combining depletion spectroscopy with resonantly enhanced multi-photon ionization time-of-flight spectroscopy.[2] The dipole moment of ground state levels has been determined by Stark spectroscopy and was found to be in excellent agreement with the theoretical predictions.[4]

LiCs molecules are created directly in a quasi electrostatic trap (QUEST), formed by a single-focused CO_2 laser. Rate coefficients for inelastic collisions between LiCs molecules and cesium atoms in the QUEST are measured to be between $\beta = 1.1 \times 10^{-10}$ cm^3/s and 2.4×10^{-10} cm^3/s, depending on the distribution of vibrational states. The large permanent electric dipole moment of ground state LiCs molecules also leads to a stronger coupling of the internal state to the environment via black-body radiation (BBR). The influence of BBR-driven transitions and spontaneous decay on the distribution of populated levels is investigated numerically using accurate potential energy curves and transition dipole moments. Experimental evidence for the occurrence of such redistribution processes in a trapped sample of ultracold LiCs molecules is found. State-selective detection of the molecules reveals population dynamics on time-scales which are in agreement with the theoretical model.[4]

* Work performed in collaboration with J. Deiglmayr (also at University of Freiburg, Germany), M. Repp, A. Grochola (now at University of Warsaw, Poland), R. Wester (University of Freiburg, Germany), O. Dulieu (Laboratoire Aimé Cotton, France), R. Côté (University of Connecticut, USA).

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Ultracold polar molecules - ultracold chemistry and dipolar collisions

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Polar molecular quantum gases promise to open new scientific frontiers and research directions. Due to their large electric dipole moment, polar molecules interact via long-range and anisotropic interactions. The control of these interactions provides unique opportunities ranging from the control of ultracold chemical reactions, applications to quantum information processing, novel strongly correlated quantum many-body systems to collisional control on the quantum level with external electric and magnetic fields. Here, we report on our recent experiments with a quantum gas of fermionic polar $^{40}K^{87}Rb$ molecules. We report the preparation of a near-quantum degenerate gas of rovibronic ground state molecules in a single hyperfine state and in particular in the absolute lowest quantum state - implementing full control over all internal molecular quantum degrees of freedom (electronic, vibrational, rotational and hyperfine). We discuss experimental evidence for chemical reactions at ultracold temperatures and show that simple quantum mechanical rules such as quantum statistics, single scattering partial waves, and quantum threshold laws provide the basis for understanding of the molecular loss rates at ultracold temperature. Finally, we report the observation of dipolar collisions in the polar molecular gas.

Ultracold and dense samples of ground-state molecules in lattice potentials

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We produce ultracold and dense samples of rovibrational ground state (RGS) molecules near quantum degeneracy. We first associate Cs_2 Feshbach dimer molecules out of a lattice-based Mott-insulator state loaded from an atomic Bose-Einstein condensate (BEC) of Cs atoms and then coherently transfer the molecules to the RGS by a four-photon straddle STIRAP process. With an overall efficiency of 50% into a specific hyperfine state, a molecular quantum gas state is prepared in which every second site of an optical lattice is occupied with a RGS molecule[1]. We expect that, with further optimization of the transfer procedure, a BEC of RGS molecules is possible. We also outline our efforts to produce dipolar quantum gases of RbCs in the RGS. Presently, we produce ultracold samples of RbCs Feshbach molecules in collisions of separately prepared Rb and Cs BECs.

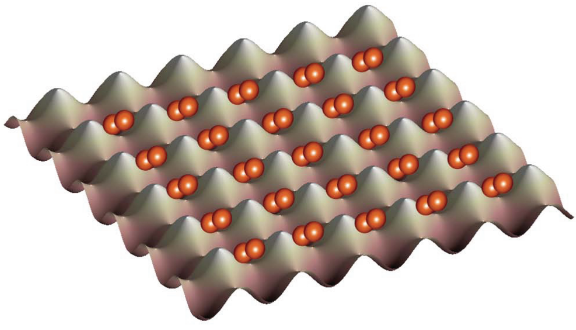

Figure 1: *Schematic drawing of molecular sample trapped in the optical lattice. The occupation probability in the central region of the lattice is near unity, while about 50% of the molecules are in a specific hyperfine level of the rovibronic ground state.*

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The Dicke quantum phase transition with a superfluid gas in an optical cavity

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A phase transition describes the sudden change of state in a physical system, such as the transition between fluid and solid. Quantum gases provide the opportunity to establish a direct link between experiment and generic models which capture the underlying physics. A fundamental concept to describe the collective matter-light interaction is the Dicke model which has been predicted to show an intriguing quantum phase transition. We have realized the Dicke quantum phase transition in an open system formed by a Bose-Einstein condensate coupled to an optical cavity, and have observed the emergence of a self-organized supersolid phase[1]. The phase transition is driven by infinitely long-ranged interactions between the condensed atoms, which are induced by two-photon processes involving the cavity mode and a pump field. We have shown that the phase transition is described by the Dicke Hamiltonian, including counter-rotating coupling terms, and that the supersolid phase is associated with a spontaneously broken spatial symmetry. The boundary of the phase transition is mapped out in quantitative agreement with the Dicke model (see Fig. 1).

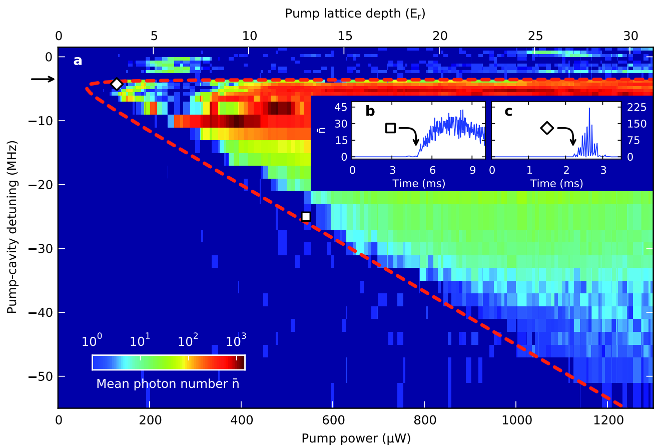

Figure 1: *Phase diagram of the self-organized atom-cavity system*

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Towards quantum magnetism with ultracold atoms

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Over the last 20 years, science with ultracold atoms has focused on motion: slowing down motion, population of a single motional state (Bose-Einstein condensation, atom lasers), superfluid motion of bosons and fermion pairs. In my talk, I will address the next challenge when motion is frozen out: Spin ordering. A two-component boson or fermion mixture can form magnetic phases such as ferromagnetic, antiferromagnetic ordering and a spin liquid. The challenge is to reach the low temperature and entropy required to observe these phenomena. I will describe our current efforts and progress towards this goal. This includes the study of fermions with strong repulsive interactions where we obtained evidence for a phase transition to itinerant ferromagnetism, and a new adiabatic gradient demagnetization cooling scheme which has enabled us to realize spin temperatures of less than 100 picokelvin in optical lattices. These are the lowest temperatures ever measured in any physical system.

Competition between pairing and ferromagnetic instabilities in ultracold Fermi gases near Feshbach resonances

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We consider the quench dynamics of a two-component ultracold Fermi gas from the weak into the strong interacting regime, where the short time dynamics is governed by the exponential growth of unstable collective modes. We show how one can find an effective interaction that takes into account both Pauli blocking and the energy dependence of the scattering amplitude near a Feshbach resonance. We use this effective interaction to study the competing instabilities towards Stoner ferromagnetism and pairing.

Inelastic Light Scattering to probe Strongly Correlated Bosons in Optical Lattices

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In condensed matter physics, inelastic scattering of waves or particles provided a very powerful method to characterize the systems under study. Neutron scattering allowed the first experimental observation of a condensate in superfluid ^{4}He [1].

As soon as experiments on ultracold quantum gases in optical lattices started to simulate many-body systems [2], theoretical papers appeared proposing to measure their dynamical structure factor through inelastic light scattering [3]. In general, inelastic light scattering allows to measure correlation functions which could identify different many-body states [4]. The response of the system to an excitation with frequency ν and momentum p is probed thanks to a two photon transition coupling two states with the same internal degrees of freedom (Bragg spectroscopy) [5]. We will report on the experimental investigation of inelastic light scattering from an array of 1D ultracold samples of ^{87}Rb atoms in an optical lattice across the superfluid to Mott Insulator transition [6]. We performed the investigation in the linear regime [7] where the excitation in the lowest band is proportional to the dynamical structure factor. Besides the frequency regions attributed to the superfluid and insulator phases, the system can be excited suggesting the presence of temperature effects and the appearance of a gapped mode in the strongly correlated superfluid regime [8]. We also investigated transitions toward excited bands coupling the many-body insulator state to free particle states and giving information on single-particle spectral functions.

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Quantum simulations with trapped ions

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Coupling internal and vibrational states of a string of trapped ions has proven to be an effective way of entangling the ions' internal states. In recent experiments, we have used this mechanism for the demonstration of high-fidelity quantum gates[1], QND measurements of spin correlations[2] and creation of large entangled states. However, these interactions are also of interest for the purpose of quantum simulations where the motional state no longer acts as an auxiallary quantum system only[3]. In this talk, I will focus on an experiment where a laser-cooled trapped ion is set to behave as a free relativistic quantum particle. This nicely demonstrates that a system acting as a quantum simulator may have completely different physical properties from the quantum system to be simulated.

The Dirac equation is a cornerstone in the history of physics, merging successfully quantum mechanics with special relativity, providing a natural description of the electron spin and predicting the existence of anti-matter. However, the Dirac equation also predicts some peculiar effects such as Kleins paradox and Zitterbewegung, an unexpected quivering motion of a free relativistic quantum particle first examined by Schrödinger. In this talk, we report on a proof-of-principle quantum simulation of the one-dimensional Dirac equation using a single trapped ion, which is set to behave as a free relativistic quantum particle[4]. We measure as a function of time the particle position and study Zitterbewegung for different initial superpositions of positive and negative energy spinor states, as well as the cross-over from relativistic to nonrelativistic dynamics. To go beyond the simulation of a free particle, we introduce linear and quadratic potentials by adding a second laser-manipulated ion. This extension enables the study of Klein tunneling[5], another relativistic effect linked to the Dirac equation.

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Universal Four-body Collisions

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The description of a few interacting particles with short-range interactions, whether atoms or molecules or nucleons, exhibits universality when the dominant length scale is the two-body scattering length. The most dramatic example of this universality in a system of three bosons or three distinguishable particles is the Efimov effect, predicted in 1970 but not observed experimentally until the impressive work of the Innsbruck group[1] in 2006. The thrust of the present work has concentrated on exploring some of the large parameter space associated with the four-body problem in this same universality regime.[2],[3],[4]

Consider the case of four-boson universality. When you add a fourth identical boson to a universal three-boson system whose two-body scattering length a is large in magnitude, it was predicted theoretically and confirmed in 2009 experimentally that there should be two bound four-body states connected with each Efimov trimer. For instance, exactly at unitarity, if the energy of a three-body universal Efimov trimer is -1 in some system of units, the energies of the two universal tetramers are predicted to be -4.58 and -1.01 in those units. These tetramer binding energies are consistent with those calculated by Hammer and Platter,[5] but to date these energy predictions have not been directly confirmed. What are more experimentally accessible are the values of the negative two-body scattering lengths at which the i-th Efimov trimer a_i^{3b} and the corresponding tetramers (with $j = 1, 2$) become unbound and turn into scattering resonances. These values were predicted in Ref.2 to obey the universal ratios $a_{i,1}^{4b}/a_i^{3b} = 0.43$ and $a_{i,2}^{4b}/a_i^{3b} = 0.90$. These phenomena have been confirmed in more than one experiment published in 2009, and supporting evidence can also be seen in the data of Ref.1.

Other predicted universality results for the four-boson system and in the two-component four-fermion system will also be discussed, along with an overview of recent experimental developments in this area.[6]

This work has been supported in part by the National Science Foundation.

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[6] C. H. Greene, Physics Today **63**, 40 (2010)

Few-body physics with ultracold gases: the fascinating case of cesium

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In 1970, Vitaly Efimov predicted one of the most counterintuitive phenomena in few-body physics. He found that a system of three strongly interacting particles supports an infinite series of giant three-body bound states, known as trimer states, with a Russian-doll-type scaling. Despite the great attention the Efimov effect has attracted in various fields, ranging from nuclear to molecular physics, its observation remained an elusive goal for 35 years.

With the advent of ultracold atomic and molecular systems with tunable interaction novel possibilities of investigation opened up. Cesium is the first species that has revealed signatures of Efimov states and related few-body phenomena. I will first give an overview of our previous observations on three-body recombination[1] and atom-dimer relaxation [2]. I will then present our results on four-body systems [3] and discuss how all these observations fit together in the Efimov scenario. Finally, I will report on the progress of our current experiments, which are dedicated to a comparison of Efimov features on different Feshbach resonances and to the search of tetramer states in dimer-dimer collisions.

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Bose-Bose mixtures in confined dimensions

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Mixtures of ultracold atomic gases are more than mere duplications of their components, whenever the interactions between the components dominate: novel phenomena arise both in few-body and in many-body physics.

We report on experiments with a mixture of two bosonic species (^{41}K and ^{87}Rb) featuring large interspecies interactions and confined by optical potentials to reduce their dimensionality. We observe scattering resonances in a mixed-dimensional configuration, where one species is confined in 2-dimensional disks while the other lives in our ordinary 3-dimensional world[1]. As we scan the free-space K-Rb scattering length by means of a suitable Feshbach resonance, we find a series of distinct peaks of atomic losses induced by inelastic collisions. We interpret these peaks as divergences of the effective, mixed-dimensional, interspecies scattering length. The degree of mixed-dimensionality is adjusted by varying the strength of the confining potential. We use a simple argument relating the energy of the open and closed channels to predict the values of magnetic field, i.e. free-space scattering length, at which the loss peaks occur.

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Timing-critical studies of atomic and molecular dynamics at the XUV FEL "FLASH"

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The new generation of linear-accelerator-based XUV and X-ray free electron lasers (FELs) represent extremely promising light sources for studying the dynamics of electronic and nuclear rearrangements in atoms and molecules. Short wavelengths guarantee high spatial resolution in diffraction experiments and facilitate deep penetration of the radiation into the electron shells, thus providing chemical specificity. High flux yields sensitivity down to the single-molecule level and high peak intensities enable remarkable steps towards nonlinear optics in the X-ray range. Finally, and most significantly the short pulse duration opens the door for utilizing well-developed X-ray tools for exploring the response of matter to an optical stimulus on the relevant time-scale.

In contrast to lasers in the visible range, however, FELs operated in the soft and hard X-ray regime are currently lacking optical resonators that would provide a selection of defined cavity modes. Instead, quantum noise is picked-up at the undulator entrance and is further amplified. As a result, an unpredictable pattern of modes is formed covering the spectral range of the FEL amplification bandwidth. The significantly structured and fluctuating temporal profiles of the pulses as well as their unstable timing require time-diagnostics on a single-shot basis. The duration and structure of XUV pulses from the Free Electron Laser in Hamburg (FLASH) are becoming accessible using a variation of the streak camera principle, where photoemitted electrons are energetically modulated in the electric field component of an intense electromagnetic terahertz wave[1]. The timing with respect to an independently generated laser pulse can be measured in an XUV/laser cross-correlator, based on a non-collinear superposition of both pulses on a solid state surface and detection of XUV-induced modulations of its reflectivity for visible light[2].

Sorting of data according to the measured timing dramatically improves the temporal resolution of experiments sampling the relaxation of transient electronic states after linear- as well as non-linear inner-shell excitation[2]. This way, the evolution of short-lived intermediates of an Auger cascade can be followed in time. The same technique unveils the dynamical details of the photo-induced molecular dissociation.

[1] U. Fruehling et al., Single-shot terahertz-field-driven X-ray streak camera, Nature Photonics 3, 523 (2009)

[2] M. Krikunova et al., Time-resolved ion spectrometry on xenon with jitter-compensated soft x-ray pulses of a free-electron laser, New Journal of Physics 11, 123019 (2009)

Attosecond imaging of molecular electronic wave-packets

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The interaction of atomic or molecular gases with intense ($I \sim 10^{14}$ W/cm^2) femtosecond lasers revealed, since the mid 80's, many unexpected highly non-linear phenomena. One of the most spectacular responses of the gas is the emission of coherent light bursts of sub-femtosecond duration, composed of harmonics of the laser frequency over a wide spectrum. In the last ten years, it became possible not only to characterize but also to control such ultrashort light pulses. This opened the way to attosecond time resolved spectroscopy, that is, to the time scale of electron motion within atoms and molecules. Besides, in 2004, Itatani *et al* [1] proposed a way to image molecular *orbitals* by a tomographic analysis of harmonic radiations generated on aligned molecules.

In the conference, we will present and analyze the results obtained for nitrogen, with a *complete* set of experimental data consisting of harmonic amplitudes *and phases*. We will discuss the validity and limitations of the model on which the method is based and demonstrate that, under certain conditions, it allows to image the molecule's HOMO ($3\sigma_g$) as well as the closest lower orbital (HOMO-1, π_u). In addition, combining the spatial and temporal aspects, we will show that the wave-packet of the electronic hole left in the molecule after ionization can be reconstructed with a temporal resolution of $\pm$ 300 attoseconds[2]. Finally, we will show how to control the light emission on a attosecond scale by orienting the molecule[3].

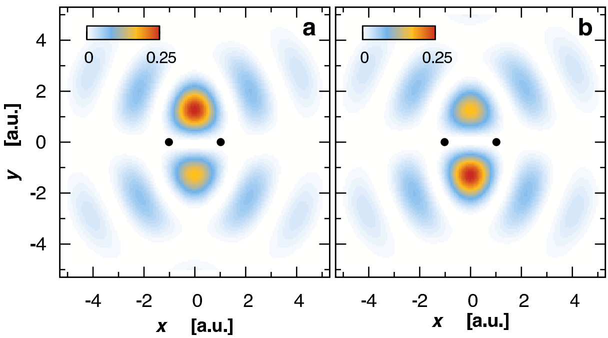

Figure 1: *(a): Squared sum and (b): squared difference of the reconstructed wavefunctions of* N_2.

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[3]W. Boutu *et al.*, Nature Phys. 4, 545-549 (2008).

Quantum Information and Quantum Metrology with Trapped Ions†

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Trapped atomic ions have been a useful system in which to study the elements of quantum information processing (QIP). The basic requirements for a quantum computer have been demonstrated along with simple algorithms. Straightforward approaches to realize scalability and fault-tolerant fidelity are being pursued; however, achieving these goals will be technically very challenging. In the near-term, quantum simulation is actively explored by several groups and simple elements of QIP are already being applied to metrology, such as in atomic spectroscopy. Prospects for large-scale QIP and some examples of near term applications will be discussed.

†The trapped-ion work at NIST involves the contributions of many people; current and recent past group members include Jason Amini[1], Jim Bergquist, Sarah Bickman[2], Mike Biercuk[3], Brad Blakestad, John Bollinger, Ryan Bowler, Joe Britton, Kenton Brown, James Chou, Yves Colombe, Hua Guan[4], David Hanneke, Jonathan Home, David Hume, Wayne Itano, John Jost, Didi Leibfried, David Leibrandt, Yiheng Lin, Christian Ospelkaus, Till Rosenband, Mike Thorpe, Hermann Uys[5], Aaron VanDevender, Ulrich Warring, Andrew Wilson and Jian Yao. We gratefully acknowledge support from IARPA, ONR, DARPA, NSA and the NIST Quantum Information Program.

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Coherently walking, rocking and blinding single neutral atoms

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Recent advances in preparation, manipulation and detection of neutral atoms have paved the way to experimentally address fundamental questions of quantum mechanics. I will report on our experimental realization of two paradgims using single neutral atoms.

In a first approach, using state dependent optical traps, we have been able to realize a quantum walk of single atoms, i.e. the quantum analogue of the classical random walk. I will report on the characterization of the properties of the quantum state created by such a walk, and the observation of the quantum-to-classical transition as decoherence turns the time evolution into a random walk. Moreover, I will show how in this system we are able to cool and control the atomic motion of atoms using microwaves. This method yields tight coherent control over an additional quantum degree of freedom with an adjustable coupling strength.

In a second model system, by deterministic insertion of atoms into a high-finesse optical resonator, we have approached a quantum non-demolition measurement of the spin state of single atoms. We have thereby observed quantum jumps of an atom between two hyperfine states. Further, I will present results on controlling the refractive index of a single atom in the resonator by coherent two-photon transitions, originating from electro-magnetically induced transparency close to the dark state resonance. In this situation right on two-photon resonance, we have found a surprising, strong cooling mechanism for atoms in the optical cavity.

Quantum memory and sensing with entangled room temperature atoms

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Room temperature spin polarized cesium gas in spin preserving environment has emerged as a promising platform for quantum state engineering and control[1]. We present two recent experiments where such systems are used for quantum communications and for quantum sensing. In the first experiment[2] we demonstrate a quantum memory for continuous variable entangled states of light which play a fundamental role in quantum information processing. We store an extensive alphabet of displaced two-mode 6.0 dB squeezed states obtained by varying the orientation of squeezing and the displacement of the states. The two components of the entangled state are stored in two atomic ensembles separated by 0.5m, one for each mode, with a memory time of 1msec. The true quantum character of the memory is rigorously proven by showing that the unconditional experimental memory fidelity 0.52 ± 0.02 significantly exceeds the benchmark of 0.45 for the best possible classical memory.

In the second experiment[3] we explore fundamental quantum limits of sensitivity of an atomic radio-frequency magnetometer. We show that the quantum state swap operation between the meter (light) and the system (atoms) is the optimal measurement strategy which allows us to suppress the influence of the shot noise of the meter on the measurement result. By applying an optimal sequence of quantum state preparation, state evolution in the magnetic field, and the backaction evading measurement we achieve the state-of-the-art sensitivity of $4.2(8) \cdot 10^{-16}$Tesla$\sqrt{Hz}$ limited by the projection noise of $1.5 \cdot 10^{12}$ atoms. We furthermore experimentally demonstrate that Einstein-Podolsky-Rosen entanglement of atoms allows to inhibit the projection noise and hence to enhance the sensitivity of the magnetometer, in particular for broadband magnetic fields.

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Title to be advised

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Quantum optics with cold quantum gases

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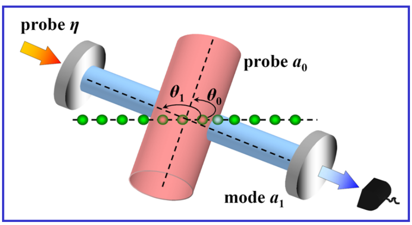
As matter influences the propagation of light waves, light can be used to manipulate matter waves. In typical situations as optical traps or cavity QED one of the two effects dominantes. However, confining a cold gas in a high finesse optical resonator creates a novel situation, where particles and photons dynamically influence their motion by momentum exchange on equal footing. The particles create a dynamic refractive index diffracting the light waves, which interfere and in turn form structured optical potentials guiding the particles motion. The ultimate limit of a quantum degenerate gas in an optical lattice inside a cavity represents a key model for *quantum optics with quantum gases*, where a quantum description of both light and atomic motion is equally important. Due to the dynamical entanglement of atomic motion and light, the measurement of the scattered light detects atomic quantum statistics and projects the many-body atomic state. For a generic case we present an analytical solution for this measurement dynamics valid for macroscopic Bose-Einstein condensates (BEC) with large atom numbers. The theory can be well applied for optical large optical lattices or even a BEC in a double-well potential.[1]
Beyond measurement dynamics we study the selfconsistent light forces on high field seeking atoms between two mirrors. Above a certain threshold illumination intensity the particles order in a regular crystalline structure, where they form ordered periodic patterns with Bragg planes optimally coupling the pump laser into the resonator.[2] At T 0 this model shows a quantum phase transition analogous to the Dicke phase transition and the resulting atomic state exhibits typical characteristics of a supersolid.



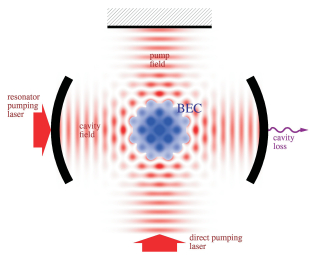


Figure 1: *a) Scheme for optical probing of atoms in a lattice b) Selforganized distribution of a BEC in an optical lattice*

The work was supported by the Austrian Science Fund FWF (P20391 and F4013).

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Optical detection of a single atom without spontaneous emission

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The measurement of microscopic quantum systems is usually accompanied by an irreversible energy exchange between the quantum system and a macroscopic apparatus. However, this is not a fundamental requirement of quantum mechanics, which allows measurements without heating. Reaching this limit of minimum measurement backaction is of primary importance for quantum information applications. For qubits encoded in the internal states of single atoms or ions, most readout methods rely on measuring their response to optical excitation using either resonant light, as in the shelving technique, or far off-resonance illumination. In these methods, information gain is inherently accompanied by heating due to the fact that at least one spontaneous emission is required to infer the qubit state. This talk will present a cavity assisted atomic state readout with almost no photon scattering. The atom-cavity system is in the strong coupling regime, such that each photon reflected or transmitted by the cavity carries a significant amount of information on the atomic state. We experimentally quantify this information in a quantum Zeno type experiment and also measure the atomic spontaneous emission rate during detection. The results show that most of the information is carried by photons leaving the cavity without having been scattered by the atom. Since our measurement apparatus detects a significant fraction of these photons, we perform a highly efficient qubit read-out: the number of spontaneous emissions is one order of magnitude below the lower limit of an ideal shelving detection scheme with the same detection efficiency.

Quantum nonlinear optics with single atoms and single photons

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The dipole oscillator is familiar to most of us because it allows capturing essential phenomena without deep knowledge on atomic physics. This description of an atom predicts that a spectral line excited near resonance is largely Lorentzian in shape whereas the statistics of the emitted radiation would barely reflect the statistics of the incoming field. When dealing with a two state level, the statistics of an incoming coherent field become antibunched, owing to the inability for the atom to absorb two photons at once. How are electromagnetic fields modified when a single atom is now strongly coupled to single photons? I will discuss experiments in our laboratory where the photon correlations, as defined with mathematical tools adapted to spectroscopy, can be tuned from antibunching to bunching, together with the predictions of optical nonlinearities such as squeezing. Such phenomena are so far understood only when quantizing light at the forefront of the theory, not within a semiclassical theory with atoms quantized and classical fields. Feedback control techniques for optimal control of atomic motion will also be discussed.

This research area, named cavity quantum electrodynamics, is investigated by us as well as by several groups worldwide with real atoms coupled to microwave or optical photons. But recent years have brought the demonstration that the very same physics can be studied in a solid-state architecture, nicknamed circuit quantum electrodynamics, where now artificial atoms made of Josephson junctions are coupled to on-chip superconducting resonators. Such fields of research made spectacular progress in the past years, and it is remarkable that they share the same concepts, whereas they explore different regimes with essentially different techniques. If time is left in my talk, I will discuss a strong European Marie-Curie action, dubbed CCQED (Circuit and Cavity Quantum Electro-Dynamics) that will bridge the aforementioned communities to share, pursue and diffuse the benefits of collaborations in the science of elementary quanta. A first realm is to strongly couple a deterministic number of particles to few photons to generate multi-particle correlated states, perform quantum state transfer between particles mediated by photons or to implement nonlinear photonics. A second realm is to build novel instruments to respond to two main demands of general utility; (i) fast-processing electronic plug-and-play devices, and, (ii) highly stable optical frequency references.

Cavity QED with Superconducting Circuits: Measuring Microwave Photon Correlations

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At optical frequencies the radiation produced by a source, such as a laser, a black body or a single photon emitter, is frequently characterized by analyzing the temporal correlations of emitted photons using single photon counters. At microwave frequencies, however, there are no efficient single photon counters yet. Instead, well developed linear amplifiers allow for efficient measurement of the amplitude of an electromagnetic field. Here, we demonstrate first and second-order correlation function measurements of a pulsed microwave frequency single photon source integrated on the same chip with a 50/50 beam splitter followed by linear amplifiers and quadrature amplitude detectors[1]. We clearly observe single photon coherence in first-order[2] and photon antibunching in second-order correlation function measurements of the propagating fields.

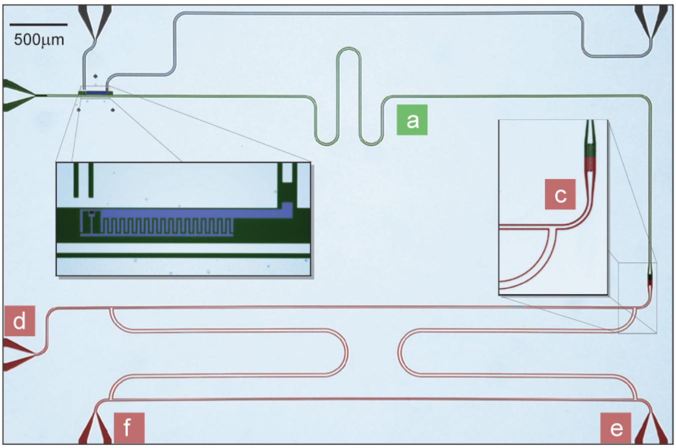

Figure 1: *Superconducting coplanar waveguide resonator (green) realizing resonant mode a interacting with integrated superconducting qubit (left inset). Output mode c is coupled into the beam splitter (red) with mode d in the vacuum state and output modes e and f. Four $\lambda/4$ sections of waveguide with impedance ratio $1/\sqrt{2}$ (see right inset) realize the beam splitter.*

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Quantum opto-mechanics in the strong coupling regime

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Micro- and nanomechanical resonators are gradually becoming available as new quantum systems. Their size and mass provide access to a completely new parameter regime for macroscopic quantum experiments[1]. We have recently demonstrated strong coupling between light and a micromechanical system[2]. This provides a new level of quantum optical control over mechanics by accessing optomechanical interactions beyond the rotating wave approximation[3].

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From cavity electromechanics to cavity optomechanics

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With the ability to harness radiation pressure forces in a cavity, researchers are rapidly progressing toward a tangible harmonic oscillator whose motion requires a quantum description. Challenges include freezing out the thermomechanical motion to leave only zero-point quantum fluctuations and, equally importantly, realizing a Heisenberg-limited displacement detector. A unique feature of cavity mechanics is that a wide variety of systems employing the same concepts are proceeding in parallel. Mechanical objects with masses from grams to picograms are being cooled by light from the optical to microwave domain. I discuss two cavity mechanics systems, one electromechanical[1] and one optomechanical[2]. Despite their differences, the nanomechanical objects utilized are similar in that they both rely upon applied tension[3]. Historically nanomechanics has been based upon flexural resonators, but by increasing tension to the point where they become "nanostrings" or "nanodrums", one can significantly increase the Q-frequency product compared to the bath temperature as well as facilitate realizing the resolved-sideband regime. I will outline progress towards ground state cooling in both systems and towards understanding the quality factors of nanostrings of various materials. Separately, in the quantum limit these systems both represent new motional quantum resources that could add to the success of trapped ions. Together, these pursuits could lead to a nanodrum capable of coupling simultaneously to both microwave and optical cavities. This along with many-photon strong coupling could provide the unique ability for quantum-state transfer between microwave and optical photons[4].

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[4]Collaboration with Konrad Lehnert.

Superfluidity in polariton ensembles

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In a semiconductor quantum well, excitons, which are bound electron-hole systems have similarities with cold atoms in a two-dimensional trap. When the quantum well is embedded in a high finesse GaAs microcavity, the strong coupling regime between excitons and light is reached at low temperature (4K), forming exciton-photon mixed quasi-particles called polaritons. Thanks to their photonic component, polaritons can be coherently excited by an incident laser field and detected through the emitted light. Thanks to their excitonic component, polaritons have binary interactions, which can modify their dispersion curve. These properties have allowed to demonstrate nonlinear and quantum optical effects in the microcavity emission.

Here, we have studied the motion of the polariton fluid injected into a planar microcavity by a resonant laser. In the presence of static defects, the response of the system is predicted using a linearized theory analogous to the Bogoliubov theory of the weakly interacting Bose gas[1]. Superfluidity of the polariton fluid should manifest itself as a quenching of the usual resonant Rayleigh scattering intensity (Landau criterion).

By varying the density of polaritons, we have demonstrated superfluidity in a quantum fluid of exciton-polaritons[2]. When the pump intensity is increased, we have observed that the system goes from a non-superfluid regime in which a static defect creates a perturbation in the moving fluid to a superfluid one, in which the polariton flow is no longer affected by the defect. When the flow velocity is increased (by increasing the angle of incidence of the pump laser) till the supersonic regime, superfluid propagation is replaced by the appearance of a Cerenkov-like perturbation produced by the defect, in agreement with theoretical predictions.

This system can be considered as a realization of a photon fluid with repulsive photon-photon interactions in the nonlinear cavity, which can exhibit a superfluid state of light[3]. These new effects are also quite similar to the ones observed in ultra-cold atomic ensembles. In addition, in the same way as in atomic condensates, the potential landscape seen by the polariton fluid can be engineered, using potential barriers created by polarized light beams, the shape and the height of which can be controlled at will. This opens the way to the study of polariton fluids in two, one or zero dimensions, trapped in specific geometries or submitted to random potentials [4].

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Thermalization of a two-dimensional photonic gas in a 'white-wall' photon box

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Bose-Einstein condensation has been experimentally demonstrated in numerous physical systems by now. The perhaps best known example of a bosonic gas, blackbody radiation, however, exhibits no Bose-Einstein condensation at low temperatures. Instead of collectively occupying the lowest energy mode, the photons disappear in the cavity walls when the temperature is lowered (vanishing chemical potential). Chiao et al. proposed to achieve a low-temperature phase transition in a nonlinear resonator configuration[1], where the freezing out of one dimension is accompanied with the photon acquiring a non-zero effective mass. Thermal equilibrium of the two-dimensional photon gas was sought from photon-photon scattering similarly to atom-atom scattering in atomic physics BEC experiments; however the weak photon-photon interaction in available nonlinear materials has so far prevented a thermalization.

Here we report on evidence for a thermalized two-dimensional photon gas with freely adjustable chemical potential. Our experiment[2] is based on a dye filled optical microresonator, acting as a white-wall box for photons. Thermalization is achieved in a photon number-conserving way by photon scattering off the dye-molecules, and the cavity mirrors both provide an effective photon mass and a confining potential - key prerequisites for the Bose-Einstein condensation of photons. As a striking example for the unusual system properties, we demonstrate a yet unobserved light concentration effect into the centre of the confining potential. Furthermore the current experimental scheme may also be extendable to atom-light quasi-particles[3].

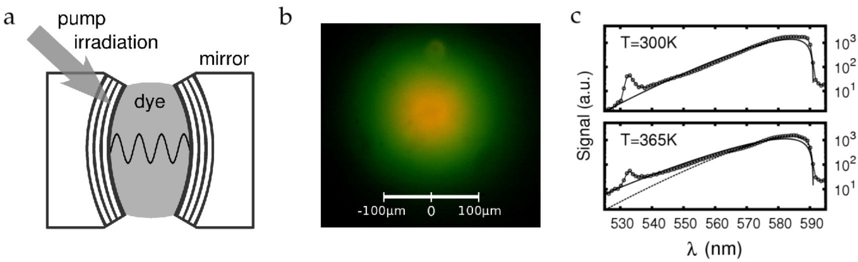

Figure 1: *(a) Simplified experimental scheme. (b) Image of the radiation emitted along the cavity axis at room temperature, showing a shift towards shorter (higher energetic) optical wavelengths for off-axis radiation. (c) Spectral distribution (circles) for two temperatures showing Bose-Einstein distributed photon energies (solid lines).*

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Demonstration of a CNOT gate and deterministic entanglement of two neutral atoms using Rydberg blockade

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We demonstrate a neutral atom CNOT gate using Rydberg state mediated interactions. The CNOT gate is demonstrated using two different protocols: a standard H - C_Z - H sequence, and a controlled amplitude swap. The gate was used[1] to create approximations to Bell states with a fidelity very close to the threshold for on-demand entanglement. Correcting for atom loss we demonstrated *a posteriori* entanglement with a fidelity of F = 0.58. Recent improvements to the experiment have now resulted in the ability to prepare all computational basis states with an average fidelity of 0.97. Using the improved apparatus we have demonstrated a CNOT gate with truth table fidelity of F = 0.91 and two-qubit entanglement fidelity as measured by observation of parity oscillations of F = 0.73$\pm$0.1 without correction for atom loss during the gate operation[2]. This is more than 2σ above the threshold for entanglement of 0.5 and is the first demonstration of deterministic two-atom entanglement using Rydberg blockade. Prospects for scaling to multi-qubit quantum logic operations[3] using a 2D array of trapped atoms will be discussed.

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Quantum information processing with neutral atoms using Rydberg blockade.

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We describe and analyse the generation of entanglement between the ground states of two individual ^{87}Rb atoms, which are held in two optical tweezers separated by 4 μm. The entanglement scheme relies on the Rydberg blockade effect, which prevents the simultaneous excitation of the two atoms to a Rydberg state. The entangled state is generated in about 200 ns using pulsed upwards and downwards two-photon excitation, as shown on the figure below.

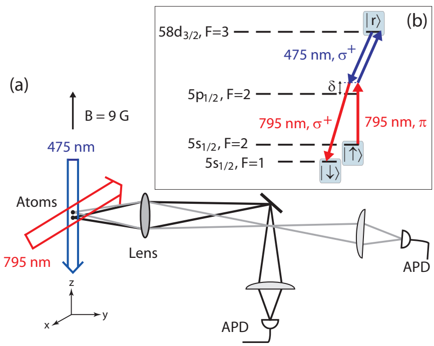

Figure 1: *Experimental setup. (a) Two atoms are held at a distance of 4 μm in two optical tweezers formed by focused laser beams at 810 nm (not shown). (b) Atomic level structure and lasers used for the excitation towards the Rydberg state. The 475 nm laser and the two 795 nm lasers are tuned to the two photon transitions from $|\uparrow\rangle$ to $|r\rangle$ and from $|r\rangle$ to $|\downarrow\rangle$.*

Provided that the atomic motion is frozen during the sequence, and that the upwards and downwards lasers are propagating in the same directions, this scheme deterministically produces the maximally entangled Bell state

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle + |\uparrow,\downarrow\rangle). \tag{1}$$

In practice, 61% of the initial pairs of atoms are still present at the end of the entangling sequence, and the measured fidelity of these pairs is 75 % with respect to $|\Psi^+\rangle$. We will discuss possible applications of this scheme for quantum information processing[1].

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