Poster Session III

Thursday, July 31
4:15 pm – 6:00 pm
Wilbur Cross Building, Reading Rooms

Bose Gases

Cold Molecules

Trapped ions

Intense Fields and Ultrafast Phenomena

Other

Large magnetic storage ring and beamsplitter for BECs

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Bose-Einstein condensates are stored in a 10 cm diameter vertically oriented magnetic ring trap.[1] After two revolutions in the ring the radial density distribution of the BEC is bimodal with the coolest (condensed) fraction having a fitted radial temperature of 10 nK and low loss propagation has been observed over a total distance of $\approx$ 2 m. BECs at the exact top of the ring are split into two counter-rotating clouds which are recombined after one revolution. The ring is ideal for studying condensate collisions (at 1.4 m/s$=$ 20 mK) and Sagnac interferometry (the enclosed area is an integer multiple of 7200 mm^2).

[1] A.S. Arnold, C.S. Garvie, and E. Riis, Phys. Rev. A 73, 041606(R), (2006).

Observation of a 2D Bose-gas: from thermal to quasi-condensate to superfluid

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We present experimental results on a Bose gas in the quasi-2D geometry near the Berezinskii, Kosterlitz and Thouless (BKT) transition temperature. By measuring the density profile, in situ and after time of flight, and the coherence length of the gas, we identify different states of the gas. In particular, we observe that the gas develops a bimodal distribution without long range order, which we identify as the quasi-condensed non-superfluid phase. In this state, the gas presents a longer coherence length than the thermal cloud, but shorter than that of the superfluid. Experimental evidence seems to indicate that we also observe the transition towards superfluidity (BKT transition), where we observe a clear discontinuity in the rate of change of the width of the narrow peak for short time-of-flight and the sudden appearance of a trimodal distribution at long time of flight.

Theory of Bose-Einstein condensate interferometry

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Bose-Einstein condensates (BEC) in cold atomic gases are a quantum system on a macroscopic scale. At near zero temperature essentially all bosons occupy a small number of single particle modes – in the simplest situations only one mode. Interferometry using BECs (such as splitting a trapped BEC into two traps and then recombining the BECs) offers a possible precision improvement given by the square root of the boson number. For non-interacting bosons and isolated BECs, the quantum correlation functions [1] describing interference experiments display clear interferometric effects. However, even for isolated BECs, internal boson-boson interactions can still result in de-phasing (associated with transitions within condensate modes) and decoherence effects (associated with transitions out of condensate modes) that degrade the interference pattern.

A theory of decoherence and dephasing effects has been developed for BEC interferometry using a phase space method where the density operator is represented by a phase space distribution functional [2], with highly occupied condensate modes described via the Wigner representation and the basically unoccupied non-condensate modes via the positive P representation [3] [4]. The theory has now been generalised to apply to an interferometry regime where up to two condensate modes can have a macroscopic occupancy, as may occur in double-well BEC interferometry. A mean field theory for treating dephasing effects based on a two-mode approximation [5] has previously been developed, leading to generalised coupled Gross-Pitaevskii equations for the mode functions. For the new phase space treatment allowing also for decoherence effects, Ito stochastic equations for condensate and non-condensate fields have been obtained from Fokker-Planck equations for the distribution functional after applying truncation approximations. Stochastic averages then give the quantum correlation functions.

[1] R. Bach and K. Rzazewski, "Correlation functions of cold bosons in an optical lattice", Phys. Rev. A 70, 063622 (2004).

[2] M. J. Steel, M. K. Olsen, L. I. Plimak et al, "Dynamical quantum noise in trapped BECs", Phys. Rev. A 58, 4824 (1998).

[3] B. J. Dalton, "Theory of Decoherence in Bose-Einstein Condensate Interferometry", J. Phys: Conference Series 67, 012059 (2007).

[4] S. E. Hoffmann, J. F. Corney and P. D. Drummond, "Hybrid phase-space simulation method for interacting Bose fields", In Press, Phys. Rev. A.

[5] B. J. Dalton, "Two-Mode Theory of Bose-Einstein Condensate Interferometry", J. Mod. Opt. 54, 615 (2007).

All-optical production of chromium Bose-Einstein Condensates.

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We report on Bose-Einstein condensation of chromium atoms in a crossed optical-dipole trap. This achievement should allow us to study the effect of large dipole-dipole interactions in the Bose-Einstein condensate (BEC), related to the large magnetic moment of Cr atoms. In our experiment, both ^{52}Cr and ^{53}Cr atoms can be simultaneously cooled and trapped [1]. To reach BEC with ^{52}Cr, we first accumulate ^{52}Cr atoms in an optical dipole trap from a magneto-optical trap. To limit light-assisted collisions, we optically pump the atoms into metastable states during the loading of the trap. To optimize the loading, and to trap all Zeeman states, we apply fast radio-frequency sweeps to the atoms, so that their spin state alternates between opposite values. This averages out magnetic forces acting on the atoms[2], which improves the loading rate by a factor of roughly 5. We then repump the atoms to their absolute ground state, and perform evaporative cooling in a crossed optical dipole trap, to reach Bose-Einstein condensation after 14 s[3].

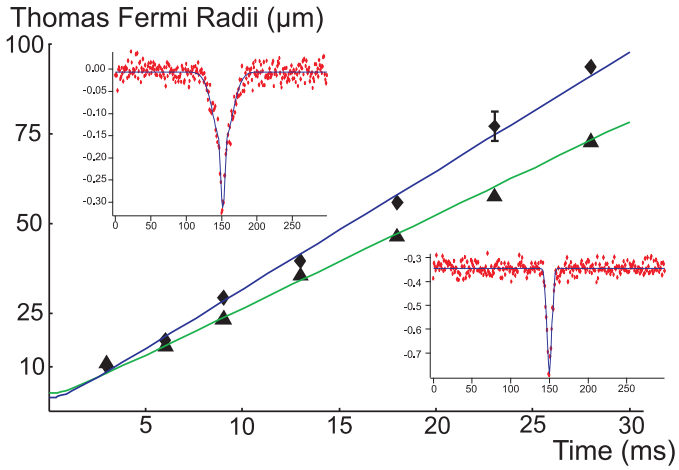

Figure 1: *Evidence for BEC. We show the ballistic anisotropic expansion of the BEC after it is released from the trap, as well as two cuts through absorption images, showing (1) a bimodal distribution at 150 nK and (2) a pure BEC (at en even colder temperature).*

[1] R. Chicireanu et al., Phys. Rev. A, **73**, 053406 (2006).
[2] Q. Beaufils et al., Phys. Rev. A , **77** , 053413 (2008)
[3] Q. Beaufils, et al., Phys. Rev. A **77**, 061601(R) (2008)

Quasi-2D Bose Einstein condensation of Cooper pairs and high T_c superconductivity

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Cuprate superconductors comprise layered structures involving buckled CuO_2 planes separated by a relatively large distance $\sim 12\,A$ along the c axis. It is generally accepted that superconductivity takes place within the Cu and O planes, a short distance $\sim 0.2\,A$ apart. Although high T_c superconductors share many characteristics common to normal superconductors, it is not clear whether a BCS theory is satisfactory to explain the main differences such as their high critical temperature, or their short coherence length $\sim 10\,A$.

We propose that high-T_c superconductivity in cuprate materials may be described by means of a Bose-Einstein condensate of excited Cooper pairs constrained to propagate within quasi-2D layers of $finite\ width\ \delta$ defined by the CuO_2 planes. With that purpose, the problem of Bose-Einstein condensation is studied for low-dimensional systems satisfying a linear energy-momentum dispersion relation. Thermodynamic quantities such as number density, energy density, specific heat, and critical temperature (T_c) are evaluated as a function of δ. We show that $T_c^2 \propto \delta n_s$, being n_s the condensate density, consistently with recent experimental findings in severely underdoped cuprate materials. Furthermore, for atomic layer widths $\sim 1\,A$, a critical temperature $T_c \sim 100$ K is obtained.

Bragg scattering from a Bose-Einstein condensate near a Feshbach resonance

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Feshbach resonances have been used in a number of experiments to manipulate the inter-atomic interaction strength of bosonic atoms, and to partially convert atomic condensates into molecular condensates[1]. In a recent experiment, Papp et al.[2] have used Bragg spectroscopy to probe the behaviour of a strongly interacting Bose-Einstein condensate of ^{85}Rb, near the Feshbach resonance at 155 G. We present a theoretical model for Bragg scattering from a Bose-Einstein condensate in the vicinity of a magnetic Feshbach resonance. The model employs two fields, of which the first corresponds to atoms and the second corresponds to the pairing of atoms into molecules[3], and we tune the binding energy of the molecules to model the Feshbach resonance and the associated increase in the effective scattering length. We use a classical field Projected Gross-Pitaevskii formalism[4], and we discuss the relevance of our results in modelling the experiment of Papp et al..

[1] E. A. Donley, N. R. Claussen, S. T. Thompson and C. E. Wieman, Nature (London) **417**, 529 (2002)
[2] S. B. Papp, J. M. Pino, R. J. Wild, S. Ronen, C. E. Wieman, D. S. Jin and E. A. Cornell, arXiv:0805.0295v1.
[3] E. Timmermans, P. Tommasini, M. Hussein and A. Kerman, Phys. Rep. **315**, 199 (1999)
[4] P. B. Blakie and M. J. Davis, Phys. Rev. A **72**, 063608 (2005)

Numerical Investigation of Contrast Degradation of BEC Interferometer

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We use a single wave function description under the framework of the mean field approximation to study the dynamics of a split condensate in various types of atom interferometers using Bragg diffraction. Our goal is to explore ways to improve, or if possible, optimize the contrast of the interference signals. Two strategies are introduced to compensate for the relative shift in momenta or spatial displacement between the two recombining components due to the atomic interaction or the trapping potential by manipulating the recombination pulse. One is to introduce a time lag; the other is to introduce a frequency shift. We account for the degradation as well as the optimization of the contrast based on the wave function properties in both configuration and momentum spaces. In trapless situation, both schemes can improve the contrast in either a Mach-Zehnder (MZ) or Double-reflection (DR) interferometer[1]. In the presence of trapping, while a DR interferometer can not be fixed by either of the optimization schemes, a MZ interferometer can be improved only by the Δk scheme. In contrast, a dephasing-free interferometer[2] is very effective and the contrast of interference signal can be improved by either optimization schemes.

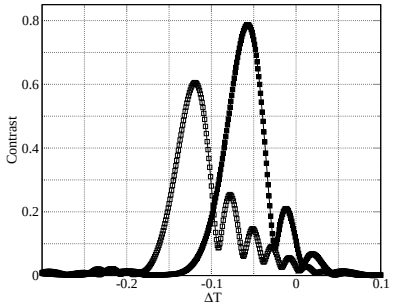

Figure 1: *The contrast of a MZ interferometer as a function of the time lag of the recombination Bragg pulse ΔT in the absence of trapping for two different atom numbers, N=3000 (solid square) and N=8000 (open square).*

[1]O. Garcia, B. Deissler, K. J. Hughes, J. M. Reeves, and C. A. Sackett, Phys. Rev. A **74**, 031601(R) (2006).
[2]M. Horikoshi and K. Nakagawa, Phys. Rev. Lett. **99**, 180401 (2008).

Yang-Yang Thermodynamics on an Atom Chip

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We investigate the behavior of a weakly interacting nearly one-dimensional (1D) trapped Bose gas at finite temperature.[1] The experiments employ a gas of ultracold ^{87}Rb atoms, magnetically trapped by a microfabricated current-carrying structure, an "atom chip". We perform in situ measurements of spatial density profiles and show that they are very well described by a model based on exact solutions obtained using the Yang-Yang thermodynamic formalism.[2] The comparison is done in a regime where other, approximate theoretical approaches fail. This constitutes the first direct comparison between experiments on the 1D Bose gas and theory based on the Yang-Yang exact solutions. Furthermore, we use Bose-gas focusing to probe the equilibrium axial momentum distribution of the gas, a quantity for which the Yang-Yang solutions do not yield a direct prediction. Our results establish a new and strong link between experiments on low-dimensional quantum gases and exact theory for interacting quantum many-body systems at finite temperature.

[1] A. H. van Amerongen et al., Phys. Rev. Lett. **100**, 090402 (2008)
[2] C. N. Yang and C. P. Yang, J. Math. Phys. (N.Y.) **10**, 1115 (1969)

Coherent modes excitation by modulation of interaction in a BEC

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The coherent states of a trapped Bose-Einstein condensate (BEC) are described by the solutions to the Gross-Pitaevskii equation (GPE). To transfer BEC from the ground to a nonground state, it is necessary to apply a time-dependent perturbation, with the frequency close to the considered transition, as a result of which the resonantly excited condensate composes an effective two-level system. The external fields, considered in the previous works [1] were formed by spatially inhomogeneous alternating trapping potentials. In this work, we proposed a new technique for creating nonground-state BEC in a trapping potential by means of the temporal modulation of atomic interactions. The main idea is to superimpose onto the BEC an uniform magnetic field with a time variation of a small amplitude. Due to the Feshbach resonance effect, such oscillatory field creates an alternating modulation of the scattering length. We show that, due this modulation, it is possible to transfer coherently atoms from the ground to a chosen excited coherent state. It is also shown that there occurs a phase-transition-like behavior in the time-averaged population imbalance between the ground and excited states. The application of the suggested technique to realistic experimental conditions is analyzed and it is shown that the considered effect can be realized for experimentally available condensates.

[1] V.I. Yukalov, E.P. Yukalova, and V.S. Bagnato,Phys. Rev. A **56**, 4845 (1997); **66**, 043602 (2002).

Vortices formation by oscillatory excitation of a BEC

E. A. L. Henn[1], J. A. Seman[1], E. R. F. Ramos[1], M. Caracanhas[1], E. P. Olimpio[1], P. Castilho[1], G. Roati[2], D. V. Magalhães[1], K. M. F. Magalhães[1], V. S. Bagnato[1]

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[2]*LENS and Dipartamento di Fisica, Universit di Firenze, INFN and CNR-INFM, Italy*

Vortices in quantum fluids are a remarkable manifestation of the quantum nature in a macroscopic scale. More than that, vortices are intrinsically related to superfluidity and hence their observation allows a convenient visual signature of such state. Vortices have been produced in many different ways. The most used technique is to use a laser beam focused to the condensate moving faster than the critical velocity [1]. Besides the already existent variety of techniques to generate vortices, new techniques can always provide new and exciting ways to explore this topic. In this work we present a new technique to nucleate vortices in a BEC, where the field generated by a set of two coils is superimposed to the trapping field creating a spherical quadrupole field, which is slightly misaligned with respect to the symmetry axis of a QUIC trap. The current in the coils is periodic in time and this oscillatory excitation couples to the condensate nucleating vortices. As a function of the amplitude of oscillation of the external magnetic field we observe several different behaviors of the condensate cloud. For small amplitudes the condensate oscillate its axis. Increasing the amplitude we observe the formation of one, two, three or more vortices in the cloud as we can see in the figure below. Above a certain amplitude of oscillation we observe uncountable vortices in every direction and this may be an evidence of a turbulent regime in the cloud. The mechanisms involved in the vortices nucleation are not completely understood. Vortices can either be due to the excitation of surface modes of the condensate due to the oscillatory motion of its center-of-mass or due to the phase imprint as described in the theoretical proposal by Mottonen et al[2].

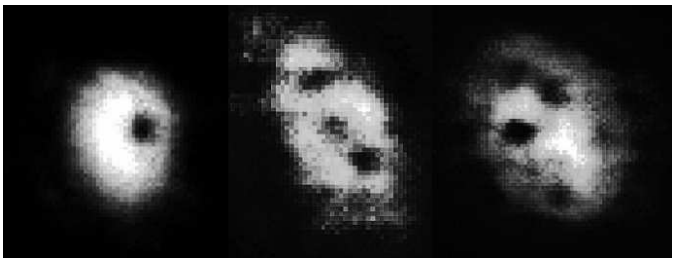

Figure 1: *Images of several vortex configurations in Bose-Einstein condensates observed with our off-axis excitation technique.*

[1]S. Inouye *et al.*, Phys. Rev. Lett. **87**, 080402 (2001)
[2]M. Mottonen *et al.*, Phys. Rev. Lett. **99**, 250406 (2007)

Corrections to Thomas-Fermi approximation for finite temperature condensate:theory and experiment

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The experiments with Bose-Einstein condensates of alkali gases have been successfully described within Thomas-Fermi approximation. At zero temperature there is no thermal cloud and and an explicit analytical relation between the condensed cloud size and parameters of the confining potential shows that[1]. $R^5 N_0^{-1} = cte$, where N_0 is the number of condensate atoms and R is the Thomas-Fermi radius. Increasing number makes the size of the cloud to scale following this relation.
At non-zero temperature, significant interaction between the condensate and the thermal cloud can modify the Thomas-Fermi relation, producing a dimension for the condensate cloud that depends on the condensate fraction. In our experimental setup, this dependence was measured and the result is shown in Fig.1. While large condensate fractions seems to show $R^5 N_0^{-1}$ tending to a constant, small fractions show significant deviation.
To explain our results we construct a Thomas-Fermi model where an explicit interaction between the condensate atoms and the thermal cloud is taken into account. We obtain a semi-classical expression to determine the chemical potential as a function of the temperature, $\mu(T)$, and hence expressing the relation $R^5 N_0^{-1}$ at different temperatures below T_c. The resulting expression is given by

$$R^5 N_0^{-1} = \frac{P_1}{\gamma}\left[1 + P_2(1-\gamma)\right], \tag{3}$$

where $\gamma = N_0/N$, P_1 is a constant depending on U_0 and ω and P_2 is a universal function. The model is shown as a solid line in Fig.1.
Acknowledgments: Fapesp, CNPq and CAPES.

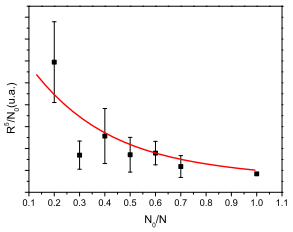

Figure 1: *Dependence of the Thomas-Fermi radius as a function of the condensed fraction showing deviation for smaller fractions of condensed atoms.*

[1]C. J. Pethick and H. Smith, Bose-Einstein Condensation in Dilute Gases, Cambridge University Press (2002)

A Smooth, Inductively Coupled Ring Trap for Atoms

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We propose and numerically investigate a scalable ring trap for cold neutral atoms that surmounts problems of potential roughness and end-effects of trap wires. A stable trapping potential is formed about an electrically isolated, conducting loop in an ac magnetic field by time averaging the superposition of the external and induced magnetic fields. The amenability of micro-fabrication of these ring traps offers the possibility for developing atom interferometry in atom-chip devices.

We consider a single, closed conducting loop of radius $r_{\rm ring}$, formed from a conductor of circular cross-section, radius $r_{\rm wire}$, immersed in a uniform magnetic field, directed perpendicular to the plane of the ring and with an amplitude that varies sinusoidally in time. This driving field and the field due to the induced current in the conductor cancel symmetrically in a ring a small distance inside the metal loop, Fig. 1. The radius of this ring varies in time, but if the magnetic potential varies at a frequency much greater than the atomic motional frequencies then a single trapping radius is found by averaging the field over one cycle [1]. Fig. 2 shows the time-averaged potential for realistic experimental parameters.

In addition to the clear benefit of no end wires the inductively coupled ring trap has the further advantage in that it surmounts the problem of trapping potential roughness caused by the deviation of the current flow from the ideal path through the wire. As was recently demonstrated, these corrugation effects are greatly reduced when ac currents are used [2]. For the configuration considered here this is of relatively minor importance as the distance from the wire to the trapping point is comparatively large, but the general concept of an inductively coupled ring trap scales to much smaller dimensions and is ideally suited for micro-fabrication.

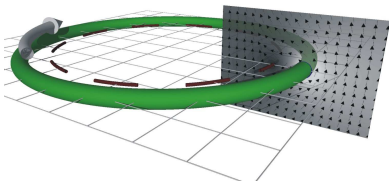

Figure 1: *Schematic of the instantaneous vector fields for the ring trap. The grey–scale in the field slice indicates field magnitude and arrows the field direction.*

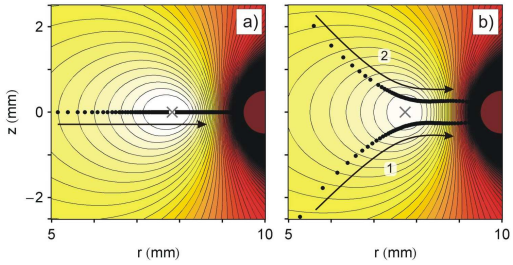

Figure 2: *Magnetic potentials;* ***a)****, no additional fields,* ***b)****, with additional dc quadrupole field. The time–averaged trap minima are marked* $\times$*, and the instantaneous zeroes of the B–field by* $\bullet$*.*

[1] P.F. Griffin, E. Riis and A.S. Arnold, Phys. Rev. A **77**, 051402, (2008).
[2] J.-B. Trebbia *et al*., Phys. Rev. Lett. **98**, 263201, (2007).

Formation of vortices in a dense Bose-Einstein condensate

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We consider a rotating dense Bose-Einstein condensate near a Feshbach resonance, where strong interaction effects appear. A relaxation method [1] is employed to study this system beyond Thomas-Fermi approximation. We use a slave-boson model [2] to describe the strongly interacting condensate and derive a generalized non-linear Schrödinger equation with kinetic term for the rotating condensate. In comparison with previous calculations, based on Thomas-Fermi approximation, significant improvements are found in regions, where the condensate in a trap potential is not smooth. The critical angular velocity of the vortex formation is higher than in the Thomas-Fermi prediction.

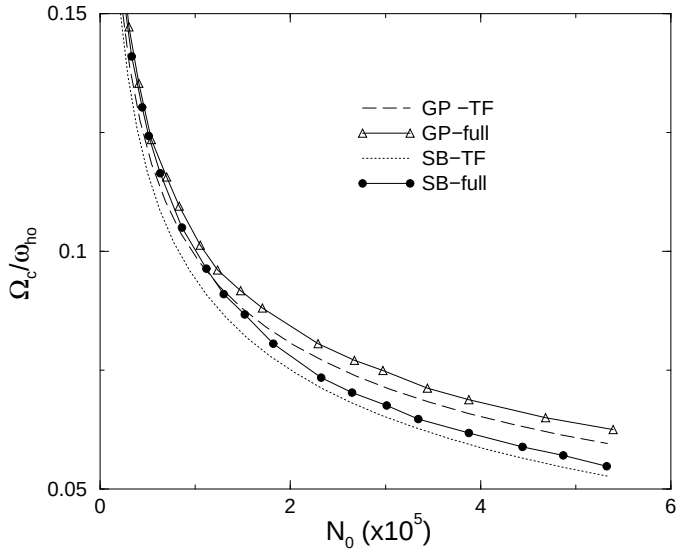

Figure 1: *Critical angular velocity calculated using the Gross-Pitaevskii (GP) equation and and slave-boson (SB) approach. Calculations where performed with Thomas-Fermi(TF) approximation and full calculations with the kinetic term (full).* N_0 *is the number of particles in the condensate. For the SB approach we used* $\beta' = 10$*, that is related to* $\beta = 1/k_B T$ *by scaling parameters.*

[1]M. Brtka, A. Gammal and L. Tomio, Phys. Lett. A 359, 339 (2006).
[2]C. Moseley and K. Ziegler, J. Phys. B: At. Mol. Opt. Phys. **40**, 629 (2007).

Experiments on Bose-Einstein Condensate of ^{87}Rb in Finite Temperatures

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We report on our experiments on the dynamics of a mixture of BEC with thermal atoms at temperatures close to critical temperature. We have developed a method of an accurate analysis of absorptive images based on a reliable method of separation of the thermal and BEC contributions. Using this method for analysis of the evolution of the atomic sample released from the magnetic trap, we observe changes of the BEC aspect ratio as a function of the BEC size (atom number) and the ratio between thermal and condensed atom numbers. For pure small condensates we observe departure from the Thomas-Fermi (TF) model but good agreement with the Gross-Pitaevskii (GP) theory (Fig. 1a). However, for mixtures of BEC and thermal atoms, the GP model works well only if the condensate fraction comprises a small number of atoms. For mixtures where the BEC fraction is sufficiently big to justify the TF approximation, we observe departures from the GP picture (Fig.1b). We attribute this departure to extra interactions between the BEC and thermal cloud[1].

This work has been performed in KL FAMO, the National Laboratory of AMO Physics in Toruń and supported by the Polish Ministry of Science.

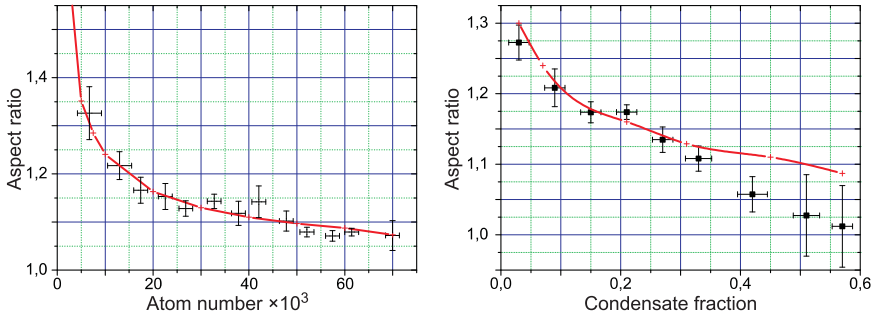

Figure 1: *Aspect ratio of (a) a pure BEC vs. the condensate size (atom number); (b) BEC in a mixture with a thermal cloud vs. the condensate fraction. Solid lines on both plots are predictions of the GP theory.*

[1]F. Gerbier, J. H. Thywissen, S. Richard, M. Hugbart, P. Bouyer, and A. Aspect, "Experimental study of the thermodynamics of an interacting trapped Bose-Einstein condensed gas," *Phys. Rev. A* **70**, 013607 (2004)

Double species Bose-Einstein condensate with tunable interspecies interactions

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[2]*CNR-INFM, Sesto Fiorentino (Firenze), Italy*

We characterize two interspecies Feshbach resonances of the Bose-Bose mixture ^{87}Rb–^{41}K, with both species in the lowest Zeeman state[1]. By means of these Feshbach resonances, occurring around 35 G and 79 G, we are able to produce a double species Bose-Einstein condensate with tunable interspecies interactions. We demonstrate that we can achieve the double BEC on both sides of the Feshbach resonance at 79 G, with attractive and repulsive interactions. While a BEC of two different species has been obtained earlier[2,3,4], we provide for the first time a double species BEC with tunable interactions. We also locate the positions of vanishing interspecies scattering length, i.e., the zero-crossings. This is especially relevant to explore the quantum phases of the double-species Bose-Hubbard model[5].

[1]These Feshbach resonances have been predicted by A. Simoni, M. Zaccanti, C. D'Errico, M. Fattori, G. Roati, M. Inguscio, and G. Modugno, Phys. Rev. A 77, 052705 (2008)

[2]G. Modugno, M. Modugno, F. Riboli, G. Roati, and M. Inguscio, Phys. Rev. Lett. 89, 190404 (2002)
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All-optical production of ^{7}Li Bose-Einstein condensation using Feshbach resonances

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Evaporative cooling of ^{7}Li atoms in a magnetic trap is a challenging task due to several reasons [1]. First, the atoms posses a relatively small scattering length and a high two-body loss rate [2]. Second, the initial phase space density is unfavorably limited by the absence of polarization-gradient cooling mechanism. Third, since the scattering length drops with increased temperature and crosses zero at $T = 8$ mK [3], the use of adiabatic compression to increase the elastic collisional rate is ineffective. In this work we show an all-optical method of making ^{7}Li condensate using the tunability of the scattering length in the proximity of a Feshbach resonance [4]. We report the observation of two new Feshbach resonances on $|F = 1, m_F = 0\rangle$ state. The narrow (broad) resonance of 7 G (34 G) width is detected at 831 ± 4 G (884^{+4}_{-13} G). Position of the scattering length zero crossing between the resonances is found at 836 ± 4 G. The broad resonance is shown to be favorable for run away evaporation which we perform in a crossed-beam optical dipole trap derived from a 100 W Ytterbium fiber laser. Starting directly from a phase space density of a magneto-optical trap we observe a Bose-Einstein condensation threshold in less than 3 s of forced evaporation.

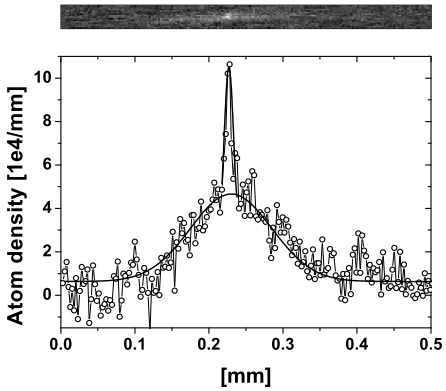

Figure 1: *On-set of BEC. In-situ absorption imaging of atoms at the BEC threshold. The thermal atomic cloud is fitted with a Bose-Einstein distribution function which yields the temperature of* 380 ± 40 *nK. The number of atoms in the BEC is* ~ 700.

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Resolving and Addressing Spin-1 BECs in Individual Sites of a CO_2-laser Optical Lattice

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We report on the direct production of an array of up to 30 independent ^{87}Rb spin-1 BECs in a large period standing wave potential created by a CO_2 laser. Using a high resolution imaging system, we optically image the individual lattice sites. Additionally, single sites are selectively addressed in a magnetic field gradient using microwave transitions. This system is ideally suited for many applications ranging from quantum information processing, to simulation of solid state systems, and to studies of condensates with small numbers.

We also present high resolution photoassociation spectroscopy of a ^{87}Rb spin-1 BEC to the 1g ($P_{3/2}$) v=152 excited molecular state manifold. We demonstrate the use of spin dependent photoassociation to experimentally identify hyperfine-rotation structure of the molecular state. These identifications are compared to a hyperfine-rotational Hamiltonian for Hund's case (c) which closely accounts for the frequency splitting of all observed hyperfine states. We have also identified the molecular states that are solely created through total spin 0 or 2 scattering channels.

Towards Dual BEC: Zeeman slower approach

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We present the features of an experimental apparatus, specially built to produce and investigate dual species atomic Bose-Einstein condensates of ^{23}Na and ^{87}Rb. The system has many interesting capabilities including a dual oven with a distillation chamber for safe handling, the ability to generate kilogauss magnetic fields, and high optical access. Our approach incorporates a Zeeman slower, capable of delivering a large flux of both Na and Rb atoms to be captured in a dual species magneto-optical trap, see Fig.1 below. Later, ^{87}Rb atoms are sympathetically cooled by large numbers of ^{23}Na atoms, evaporativelly cooled down to the quantum degeneracy. We are interested in observing quantum statistical effects, interaction tuning, and production of heteronuclear ultracold dimer molecules. Future experiments and ideas may be presented.

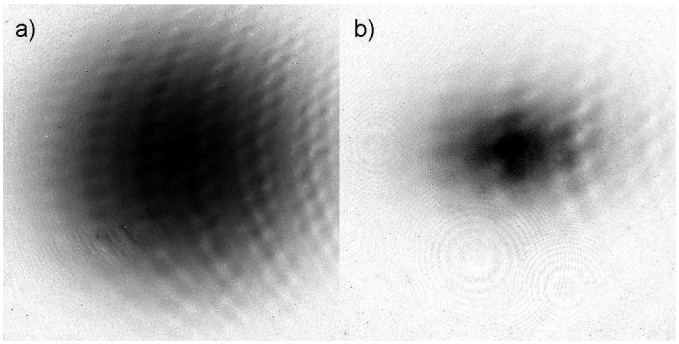

Figure 1: *Absorption images of our overlapped two species magnetic trap (MT) of:a) ^{23}Na; and b) ^{87}Rb. We have been able to load around 10^9 Na atoms and 10^8 ^{87}Rb in our MT.*

Generating Nonclassical States in Atom-Optics via Self Interaction.

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The creation of the optical laser and the development of quantum optics has allowed tests of many fundamental properties of quantum mechanics[1]. The ability to create quantum squeezing is an important prerequisite for many of these tests as it allows the creation of continuous variable entanglement between the amplitude and phase of two spatially separated optical beams. With the advent of the atom laser, there is much interest in creating a squeezed atomic beam as it allows us to revisit many of these tests using massive particles rather than photons. Atom lasers are also of interest for precision measurement. Interferometry using massive particles promises hugely increased sensitivity over that available optically. As one example, given equal enclosed area and particle flux, the sensitivity of atom interferometer gyroscopes exceeds that of photonic gyroscopes by a factor of 10^{11} [2]. A seemingly obvious route to take advantage of this feature is the use of atom lasers in interferometry. However, the fundamental limit to the sensitivity of any measurement will be the atomic shot noise. The sensitivity can be increased by quantum squeezing. Squeezing is arguably more important in an atom interferometer, as the flux cannot be increased arbitrarily.

We propose a method for generating quantum squeezing in atom-optical systems. We show that it is possible to generate squeezed atom lasers, and Bose-Einstein condensates with squeezed occupation numbers by utilising the nonlinear atomic interactions caused by s-wave scatting. We develop an analytic model of the process which we compare to a detailed multimode stochastic simulation of the system using phase space methods, and show that significant quadrature squeezing can be generated, and that this squeezing is easy to control by adjusting parameters such as the outcoupling rate. Furthermore, we show that by interfering two atom laser beams from the same condensate, we can convert quadrature squeezing into intensity squeezing in one of the beams, or intensity difference squeezing between the two beams, independent of the initial phase statistics of the condensate. Finally we show that significant squeezing can be obtained in an experimentally realistic system and suggest ways of increasing the tunability of the squeezing[3]. We propose a simple method for creating BEC's with squeezed occupation numbers, via a similar method.

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The cranked-Hartree-Fock-Bogolibov description for Fragmented Bose-Einstein Condensates

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A possibility of a fragmented Bose-Einstein condensate (FBEC) was suggested in 1982 by Nozières and Saint James, for an infinite system. The realization of the BEC in the finite trap stimulated reinvestigations of a possible FBEC in the trap. Recently, Liu et. al. pointed out that a FBEC is realized for a 2-dimensional Bose system in an isotropic harmonic trap, using the exact diagonalization technique[1].

We recently developed a computer code based on the cranked Hartree-Fock-Bogoliubov (CHFB) theory so as to calculate the yrast states of rotating ultra-cold Bose gases [2] [3]. In the CHFB theory, the creation and annihilation operators for the ground state ($c_0^\dagger$,c_0) are not set to be $\sqrt{N}$, where N is the number of atoms. Then, the quasi-particle operators $a_i^\dagger, a_i$ are given as $a_i^\dagger = \sum_\alpha U_{\alpha i} c_\alpha^\dagger + V_{\alpha i} c_\alpha$, $a_i = \sum_\alpha U_{\alpha i}^* c_\alpha + V_{\alpha i}^* c_\alpha^\dagger$, where α includes both the ground and excited states. Therefore, the ground state is not expressed as the coherent state, but as the Thoulessian ansatz $\mathcal{N} \exp(f_{\alpha\beta} c_\alpha^\dagger c_\beta^\dagger)$. Different from the Gross-Pitaevski approach, this ansatz wavefunction can represent a fragmented condensate in which macroscopic occupations are made to multiple single-particle states.

Within the framework of the CHFB theory, we developed a method called "Valence Field Expansion", which enables us to calculate matrix elements of an arbitrary 2-body interaction. [3] Using this new technique, we calculate the yrast states of interacting Bose gases in a deformed trap through the δ-type interaction. In this work, we show that the yrast state changes its nature from a fragmented BEC to a single BEC as the trap potential gets deformed. We also discuss conditions for the fragmented and single BEC to be formed in terms of the deformation of the trap and the strength of a 2-body force.

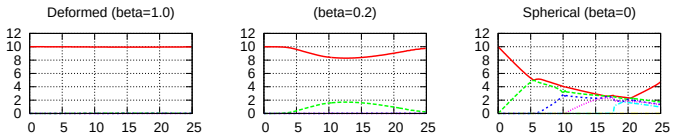

Figure 1: *Eigenvalues of the density matrix as a function of angular momentum for a rotating Bose gas with the total particle number $N = 10$. A FBEC and a single BEC are produced in the spherical (right) and deformed (left) traps, respectively.*

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Quantum Brownian Motion in a Bose-Einstein Condensate

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Classical Brownian motion is the random walk of a particle, large enough to behave classically, due to collisions with the molecules of the fluid in which it is immersed. The theoretical understanding of this process was one of the efforts that earned a Nobel Prize for Albert Einstein, and involves the fundamental connection between fluctuations and dissipation.
We propose to investigate an analogous system in which quantum mechanics must play a central rôle: A single impurity atom (or a small number) immersed in a Bose-Einstein condensate (BEC) of a different species. We refer to the behaviour of the impurity as quantum Brownian motion.
Experimental realization of such a system may be possible by using optical tweezers to place a small number of rubidium atoms in a sodium BEC, for example.
We apply quantum field-theoretic techniques and phase-space methods to investigate two questions.

- What is the behaviour of an impurity atom when placed into a BEC in a state that is localized on a scale much smaller than the extent of the BEC and that has zero average momentum? The observables we investigate in direct phase-space simulations are the position and momentum densities of the impurity, to see whether the spreading rate of the position wavepacket is influenced by its environment. Self-trapping[1], in which the impurity creates a potential minimum for itself by distorting the BEC, is seen to play an important rôle.
- What is the behaviour of the impurity when introduced with a nonzero average velocity? We have theoretical expectations concerning this problem. In Landau's picture[2], an impurity moving through a superfluid BEC has no mechanism for energy loss to phonons if the velocity is below the speed of sound for the medium. Recent experiments and theoretical investigations have called into question some of the details of this picture. An experiment[3] on laser stirring of a trapped condensate found a critical velocity for energy dissipation much less than the speed of sound due to the emission of vortices. A recent calculation[4] of the drag force on a moving (classical) obstacle in a BEC found a nonzero drag force down to zero velocity.

We investigate these questions with direct phase-space simulations, providing a completely quantum-mechanical treatment of the BEC and the impurity.

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Guided-wave atom interferometer with mm-scale arm separation

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Guided-wave atom interferometers measure interference effects using atoms held in a confining potential. In one common implementation, the confinement is primarily two-dimensional, and the atoms move along the nearly free dimension after being manipulated by an off-resonant standing wave laser beam. In this configuration, residual confinement along the nominally free axis can introduce a phase gradient to the atoms that limits the arm separation of the interferometer. We experimentally investigate this effect in detail, and show that it can be alleviated by having the atoms undergo a more symmetric motion in the guide. This can be achieved by either using additional laser pulses or by allowing the atoms to freely oscillate in the potential. With these techniques, we demonstrate interferometer measurement times up to 72 ms and arm separations up to 0.42 mm with a well controlled phase, or times of 0.91 s and separations of 1.7 mm with an uncontrolled phase.

Three-dimensional character of atom-chip-based rf-dressed potentials

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We experimentally investigate the properties of radio-frequency-dressed potentials for Bose-Einstein condensates on atom chips. The three-dimensional potential forms a connected pair of parallel waveguides[1]. We show that rf-dressed potentials are robust against the effect of small magnetic-field variations on the trap potential. Long-lived dipole oscillations of condensates induced in the rf-dressed potentials can be tuned to a remarkably low damping rate. We study a beam splitter for Bose-Einstein condensates and show that a propagating condensate can be dynamically split in two vertically separated parts and guided along two paths. The effect of gravity on the potential can be tuned and compensated for using a rf-field gradient.

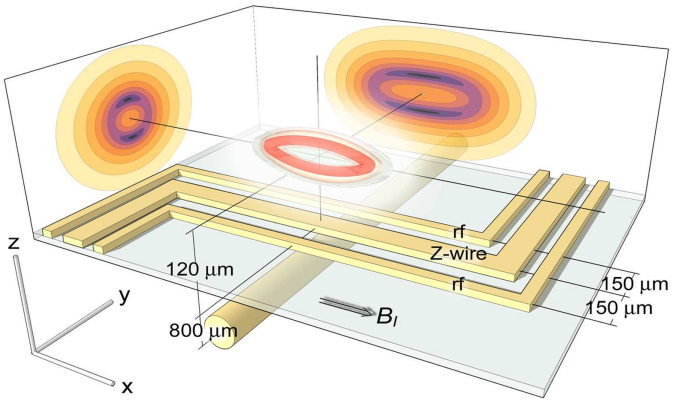

Figure 1: *Schematic of the atom chip and the rf-dressed potentials it produces. The central Z-shaped wire carries a dc current and is used together with an external bias field along y to produce a Ioffe-Pritchard magnetic microtrap. Positioned next to the Z-shaped wire are two wires which carry rf currents. Potential-energy cross-sections for vertical splitting are depicted on the back planes of the image. A sketch of the trapped atom cloud is shown in the center, above the Z-shaped wire.*

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Bragg Spectroscopy of a Strongly Interacting ^{85}Rb Bose-Einstein Condensate

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We report on measurements of the large-momentum excitation spectrum of a strongly interacting Bose-Einstein condensate (BEC). Using a magnetic-field Feshbach resonance to tune atom-atom interactions in the condensate, we reach a regime where quantum depletion of the ground state and beyond mean-field corrections to the condensate chemical potential are significant. The Bragg resonance line shift due to strong interactions was found to be significantly less than that predicted by a mean-field theory, and demonstrates the onset of beyond mean-field effects in a gaseous BEC.

A High Flux Atom Laser for Interferometry

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The atom laser, first demonstrated at MIT[1], is a promising source for atom interferometry for fundamental and practical applications. Although the quantum statistics and flux, in theory, limit the signal to noise ratio in an interferometric measurement, the classical properties, such as intensity fluctuations, frequency fluctuations and spatial mode profile often prevent an experiment from reaching its fundamental noise floor. Recent experimental studies[2,3] have shown that it is possible to get a clean spatial mode profile using an RF transition provided the outcoupling cut is applied from the bottom of the condensate. The flux of an atom laser is proportional to the outcoupling Rabi frequency and the number density of the atoms in the vicinity of the outcoupling cut. As there is an upper limit on the outcoupling Rabi frequency for classically quiet operation[4], it is desirable to outcouple from the centre of the condensate, where the number density and therefore the atom laser flux, is maximized. We show that for a Raman atom laser, in contrast to an RF atom laser, we can outcouple from the centre of the condensate and still retain a clean spatial mode[5].
In our experiment we create ^{87}Rb condensates of 5×10^5 atoms in the $F = 1, m_F = -1$ trapped state that we couple to the $F = 1, m_F = 0$ un-trapped state via an optical Raman transition[6]. The atoms then receive a momentum kick from the absorption and emission of photons. As a result, they leave the condensate quickly so that adverse effects due to the mean-field repulsion are reduced. As the kick increases, the divergence is reduced and the beam profile improved. The beam quality parameter[2] is also measured and the experimental results are compared to theoretical models finding excellent agreement.
We also report[7] on the experimental realization of a multibeam atom laser. A single continuous Raman atom laser is outcoupled from a condensate before being subsequently split into up to five atomic beams with slightly different momenta. The splitting process itself is a realization of Bragg diffraction driven by each of the optical Raman laser beams independently, which is a significantly simpler implementation of an atomic beam splitter. The multiple, nearly copropagating, coherent atomic beams resulting from this process could be of use in interferometric experiments.

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Cleaning of magnetic substates in an optical dipole trap

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We use an optical dipole trap, realized by the tight focus of a 25 Watt CO_2 laser, to cool ^{87}Rb atoms by lowering the dipole trap depth (forced evaporation) to temperatures below 100 nK. We end up with a sample of $2 - 5 \times 10^4$ degenerate atoms. By applying an asymmetric and inhomogeneous magnetic field at the end of the forced evaporation phase, prior to switching off the CO_2-laser, we are able to remove atoms in the magnetic levels $m_f \neq 0$ from the trap. The magnetic field is realized by operating anti-Helmholtz coils with unbalanced currents. We monitor this process by photographing the time-dependent emission of atoms, and by probing the residual atoms in the trap by a Stern-Gerlach experiment. We show that a complete removal of atoms in the states $m_f \neq 0$ is possible by appropriate adjustment of the magnetic field distribution. The experimental observations are supported by numerical simulations of atom trajectories in our experiment.
Our cigar shaped dipole trap has an axial Rayleigh length of ≈ 400 μm and a radial waist radius of ≈ 35 μm. The trapping force along the axial direction is the weakest and therefore the application of an inhomogeneous field provides exit ports for atoms along the axial direction when the magnetic field Zero does not coincide with the center of the dipole trap. To do our experiments, we first transfer all m_f states from a MOT into the optical dipole trap by polarization-gradient cooling. After turning off the MOT and the magnetic field we begin a phase of forced evaporative cooling over a five seconds long ramp. At the end of the ramp the dipole trap laser operates near 200 mW and is kept constant over the final 100 ms before turning off the CO_2 laser. During this period the additional magnetic force is turned on and the free fall sequence (in the presence of the magnetic field), is photographed by absorption imaging. A splitting into three clouds along the vertical direction is observed when the magnetic field is turned on when the CO_2 laser is turned off. However, by applying the magnetic field earlier the emission of atoms along the axial direction (already in the evaporation phase) is observed and shown to derive from atoms in the magnetic substates $m_f = \pm 1$ being emitted from the shallow dipole trap, as shown below.

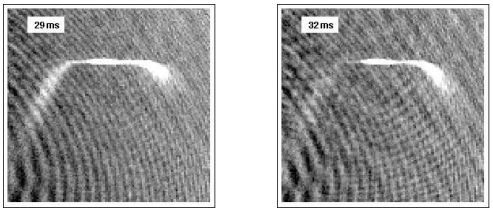

Figure 1: *Absorption pictures for two different switching times $\Delta t = \{29,\ 32\}$ ms at a fixed free fall time t_{fall} = 1 ms.*

First Determination of the Helium $2\,^3P_1 - 1\,^1S_0$ Transition Rate

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Quantum electrodynamics (QED) is one of the most rigorously tested fundamental theories of modern physics, for which the atomic energy levels of helium and heliumlike ions represent an important test bed. Helium is the simplest multielectron atom, enabling theoretical calculations to be performed with greater accuracy than for more complex species. By contrast, other atomic parameters such as transition rates are much harder to determine, both experimentally and theoretically, with accuracies often at the percent level. The behavior of the transition rates of heliumlike atoms in an isoelectronic sequence is a case in point that has received considerable theoretical attention[1,2,3]. A number of experimental determinations of the transition rates of highly ionized heliumlike species have tested these QED predictions, but there have been no published measurements of the decay of helium atoms from the $2\,^3P$ states to the ground state.

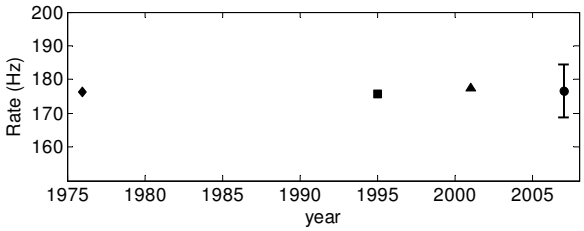

Figure 1: *(a) Historical progress of theoretical determinations for the helium $2\,^3P_1 - 1\,^1S_0$ decay rate (references shown), together with the experimental value (and uncertainty) from the present work. References 1-4, left to right.*

We present the first experimental determination of the $2\,^3P_1 - 1\,^1S_0$ transition rate in helium [4] and compare this measurement with theoretical quantum-electrodynamic predictions. The experiment exploits the very long ($\sim$1 minute) confinement times obtained for atoms magneto-optically trapped in an apparatus used to create a Bose-Einstein condensate of metastable ($2\,^3S_1$) helium. The $2\,^3P_1 - 1\,^1S_0$ transition rate is measured directly from the decay rate of the cold atomic cloud following 1083 nm laser excitation from the $2\,^3S_1$ to the $2\,^3P_1$ state, and from accurate knowledge of the $2\,^3P_1$ population. The value obtained is $177 \pm 8\ \mathrm{s}^{-1}$, which agrees very well with theoretical predictions, and has an accuracy that compares favorably with measurements for the same transition in heliumlike ions higher in the isoelectronic sequence.

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Single mode guiding of an atom laser beam

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Atoms coherently output-coupled from a Bose-Einstein condensate (BEC) form a coherent beam of matter waves, or 'Atom laser'. Like its optical counterpart, the atom laser has the potential to revolutionise future atom interferometric sensors, in which a high flux of collimated atoms is required. Most condensates are confined in a magnetic potential, where to achieve maximum flux the atom laser beam is outcoupled from the centre of the BEC. This leads to atoms in the atom laser beam probing the high density region of the BEC via s-wave interactions and experiencing a large repulsive force (so-called 'mean field' repulsion). These interactions strongly distort the atom laser beam, resulting in a far from ideal spatial profile that exhibits a double peaked structure (see Fig 1(c)) [1,2]. A method to alleviate this problem is to use an optically trapped BEC. In such case an atom laser is produced by simply turning down the optical power of the trap and letting atoms fall out of the spatial minimum of the trap where the atomic density is low. Furthermore, by not extinguishing the optical trap completely the atom laser beam experiences a weak confining potential that acts like an optical fibre to guide the atoms.

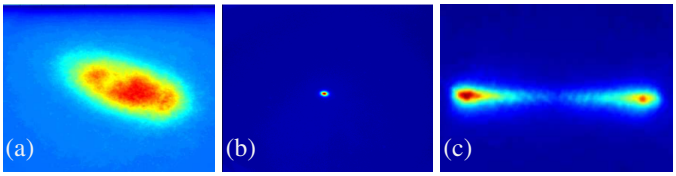

Figure 1: *(a) Spatial profile of the optically trapped BEC if no guide is implemented, (b) single mode guided profile and (c) usual He* atom laser profile. Each image is 1.1 cm by 0.8 cm.*

Here we demonstrate single mode guiding of a metastable helium (He*) atom laser using a far detuning laser beam. Atoms cooled to $\sim 1\ \mu$K in a magnetic trap are transferred to an optical trap aligned in the vertical direction, where BEC is achieved. Subsequent lowering of the optical potential by a factor of ~ 100 in 10 ms releases the atoms into the guide and they fall under gravity for 200 mm where they strike a multi-channel plate (MCP) and are imaged. The whole process is adiabatic allowing the atoms in the BEC to transfer smoothly from the ground state of the trap to the groundstate of the guide. The resulting guided profile can be compared with the more usual atom laser profile as well as the spatial profile of the optically trapped BEC if no guide is implemented (see Fig. 1).

[1] J.-F. Riou *et al.*, Phys. Rev. Lett., **96**, 070404 (2006).
[2] R. G. Dall, et al., Opt. Express, **15**, 17673 (2007).

Dynamics of a BEC in a 3D double-well potential

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A Bose-Einstein condensate in a double-well provides an elegant combination of a simple system, analytically solvable and applicable to interferometry, while still featuring rich dynamics. The competition between tunneling and on-site interactions is well described by a nonlinear Hamiltonian, similar to the Kerr Hamiltonian in optics or the Bose-Hubbard Hamiltonian in condensed matter physics, which allows for the deterministic preparation of spin squeezed and other nonclassical quantum states.

Spin squeezed states in particular have attracted much attention because they are robust, comparatively easy to produce, and permit measurements of atomic clocks and interferometers below the standard quantum limit. They can be created as number-squeezed states during the splitting of a single BEC in a double-well, a process studied both theoretically[1] and experimentally[2]. So far only indirect evidence of squeezing in a double-well has been demonstrated[2]. We directly measure the atom number statistics of a BEC in double-well and its dependence on the splitting dynamics, atom loss and atom number.

We implement a double-well on an atom chip that combines compactness, fast cycle times, and flexible trap geometries. While we currently use only one double-well, our two-layer chip design creates smooth static magnetic multi-well 3D potentials in linear and topologically connected geometries. Our chip and imaging system are compatible with small and micro BECs ranging from tens to thousands of ^{87}Rb atoms.

[1]Y. Li, Y. Castin and A. Sinatra, "Optimum Spin Squeezing in Bose-Einstein Condensates with Particle Losses", Physical Review Letters **100**, 210401 (2008)

[2]G. Jo et al., "Long Phase Coherence Time and Number Squeezing of Two Bose-Einstein Condensates on an Atom Chip", Physical Review Letters **98**, 030407 (2007)

First realization of Bose-Einstein condensation in microgravity

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[2]*Institute of Quantum Optics, Leibniz University of Hanover, Germany*
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Since the possibility of trapping and cooling neutral atoms, ultracold quantum degenerate gases have shifted boundaries in a growing field of modern physics. The current developments in the domain of atom optics lead to an utilization of ultracold quantum matter techniques in unique practical applications as high-precision atomic clocks, atom interferometer technologies and inertial sensing instruments for gravity field mapping, underground structure detection, autonomous navigation, as well as precision measurements in fundamental physics. The expectations of even higher precision measurements can be performed by arbitrarily extending the time of unperturbed evolution of quantum degenerate systems. In respect thereof weightlessness provides an outstanding basis for such applications and measurements.

We report on the first experimental demonstration of rubidium Bose-Einstein condensates in the environment of weightlessness at the earth-bound short-term microgravity laboratory Drop Tower Bremen, a facility of ZARM ("Center of Applied Space Technology and Microgravity") - University of Bremen. This pilot project is performed within the QUANTUS ("Quantum Systems in Weightlessness") collaboration[1,2] to study the possibilities of Bose-Einstein condensation experiments in free fall on earth and the feasibility of ultracold quantum matter techniques on space-based platforms. Our approach is based on a compact, mobile, robust and autonomous operating drop capsule experiment to currently realize weightless Bose-Einstein condensates with longest time of flights (up to 1 second) and adiabatic expansions to very shallow traps (lower than 20 Hz). For this purpose the drop capsule setup has to withstand decelerations of around 50g on every free fall. So far, we have successfully accomplished more than 150 drops with the QUANTUS apparatus since the beginning of November 2007.

The pilot project QUANTUS gratefully acknowledges the support from the DLR ("German Aerospace Center").

[1] A. Vogel et al., Appl. Phys. B 84, no. 4, 663-671 (2006)
[2] W. Lewoczko-Adamczyk et al., IJMPD 16, no. 12b, 2447-2454 (2007)

Universality of Bose-Einstein condensation of weakly interacting multi-component atomic gas close to high symmetry point

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We examine a possibility that BEC of N-component weakly interacting Bose gas with the symmetry group $\mathrm{O}(2N)$ broken down to a subgroup is preempted by spontaneous breaking of this subgroup. This implies condensation of a quadratic form $M_{ab} = \langle \Psi_a^* \Psi_b \rangle$ (or $M_{ab} = \langle \Psi_a \Psi_b \rangle$) before atomic (bosonic) fields $\psi_a = \langle \Psi_a \rangle, a = 1, 2, ..., N$ become condensed. As an example, phase separation could take place before BEC in a spinor $S = 1/2$ two-component gas.

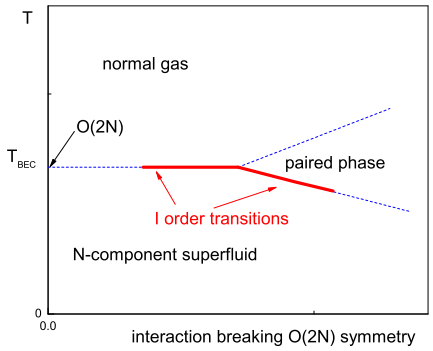

Figure 1: *Generic phase diagram of weakly interacting BEC*

Generic phase diagram,Fig.1,is obtained by introducing Landau free energy functional $H(M_{ab}, \psi_a)$. In particular, there is a term $\sim M_{ab}\psi_b^*\psi_a + c.c.$ (or $\sim M_{ab}\psi_b^*\psi_a^* + c.c.$)[1]. It is important that for small symmetry breaking interactions, the transition is *always of II order* in the universality class dictated by the structure and symmetry of the order parameter and Hamiltonian. Another important aspect is that the intermediate phase (we call is *paired*) may not be present in a particular model because specific microscopic parameters just don't map onto the corresponding region of the Landau functional. As a specific example, we have performed Monte Carlo simulations of spinor $S = 1/2$ Bose gas with the tendency to phase separation and has shown that its phase diagram, while featuring II and I order lines of BEC transitions, does not contain *paired* phase.

[1]A.B. Kuklov, N.V. Prokof ev, B.V. Svistunov, PRL **92**,050402-1(2004)

Towards thermal melting of a vortex lattice in a rotating 2D BEC

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Compared to 3D systems, superfluids in a 2D geometry are characterized by much larger phase fluctuations. At very low temperatures rotating superfluids in 2D present a regular vortex crystal. As the temperature of the system increases, the vortex crystal undergoes a structural phase transition and melts into a liquid phase.

We are experimentally investigating the transition between the vortex crystal phase and the vortex liquid phase in a rotating 2D BEC as the temperature of the system changes.

A blue-detuned 1D vertical optical lattice (see Figure 1) is used to slice a 3D condensate into many layers and by increasing the lattice depth one can achieve the quasi-2D regime for individual layers. The superfluid can be kept under rotation in a controlled way using a weak rotating 2D optical lattice as a stirring potential. A slice imaging technique is employed in order to selectively image a single 2D layer from the top and be able to directly observe its vortex pattern.

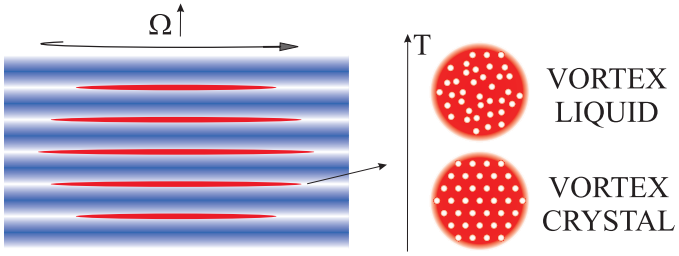

Figure 1: *Rotating BEC in a blue-detuned 1D vertical optical lattice (**left**). Each single rotating pancake is expected to present a vortex pattern (**right**) that will be more (crystal phase) or less (liquid phase) regular, depending on the temperature of the whole system.*

Creating a supersolid in one-dimensional Bose mixtures

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We identify a one-dimensional supersolid phase in a binary mixture of near-hardcore bosons with weak, local interspecies repulsion. We find realistic conditions under which such a phase, defined here as the coexistence of quasi-superfluidity and quasi-charge density wave order, can be produced and observed in finite ultra-cold atom systems in a harmonic trap. Our analysis is based on Luttinger liquid theory supported with numerical calculations using the time-evolving block decimation method. Clear experimental signatures of these two orders can be found, respectively, in time-of-flight interference patterns, and the structure factor $S(k)$ derived from density correlations.

Toward sub-shot-noise fluctuations in coherently split quantum degenerate gases

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[2]*Atominstitut der Österreichischen Universitäten, TU Wien, A1020 Vienna, Austria*

We have performed direct measurements of atom number at two output ports of a coherent beam-splitter for a Bose-Einstein condensate (BEC), observing atom-number fluctuations at the shot-noise level. Starting from a BEC in a chip-based magnetic trap, the splitting is achieved by adiabatic transformation from a single-well to a double-well using an oscillating (rf) field[1]. We perform direct detection of atom number at each output port via optical absorption imaging, as shown in Fig. 1.
The double-well BEC system is analogous to a bosonic Josephson junction[2], providing a link with condensed matter physics. One potential application is atom interferometry in confined geometries, of great interest for precision measurements such as sensing local fields and their gradients (gravitational or electromagnetic). Our goal is to observe sub-shot-noise fluctuations[3] directly in the number difference between the two output wells, and study their dependence on splitting dynamics, and trap geometry. We present our progress to date, including characterization of the double-well potentials, evaluation of detection sensitivity, rf field amplitude calibration, and a recent redesign and replacement of our atom chip. We also discuss prospects for a complementary measurement with degenerate fermions.

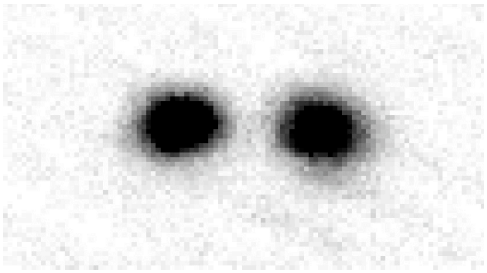

Figure 1: *Absorption image of a coherently split BEC. Separation of the clouds is about* $100\ \mu\mathrm{m}$*, and the total atom number in both clouds is* $N \approx 8 \times 10^3$*. Our detection sensitivity is at the level of* 40 *atoms, limited by optical shot noise.*

[1]T. Schumm et al, Nature Physics **1**, 57 (2005).
[2]R. Gati et al, Appl. Phys. B **82**, 207 (2006).
[3]G.-B. Jo et al, Phys. Rev. Lett. **98**, 030407 (2007).

Condition for Dynamical Instability of a Trapped Bose–Einstein Condensate with a Highly Quantized Vortex

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We consider a trapped Bose-Einstein condensate (BEC) with a highly quantized vortex. For the BEC with a doubly, triply, or quadruply quantized vortex, the numerical calculations have shown that the Bogoliubov-de Gennes equations, which describe the fluctuation of the condensate, have complex eigenvalues [1]. The presence of the complex eigenvalues is interpreted as a sign of the dynamical instability. This instability is associated with the decay of the initial configuration of the condensate and can occur even at zero temperature, contrary to the Landau instability. In this study, we show an analytic expression of the condition for the existence of complex modes, using the method developed by Rossignoli and Kowalski[2] for the small coupling constant. To derive it, we make the two-mode approximation. With the derived analytic formula, we can identify the quantum numbers of the complex modes for each winding number of the vortex[3]. Our result is consistent with those obtained by the numerical calculation in the case that the winding number is two, three, or four. Furthermore, the three-mode analysis is also performed, and it is confirmed that the condition for the existence of complex modes is not modified. Our conclusion is that the complex modes always exist when the condensate has a highly quantized vortex[3].

[1]H. Pu, C. K. Law, J. H. Eberly, and N. P. Bigelow, Phys. Rev. A **59**, 1533 (1999); M. Möttönen, T. Mizushima, T. Isoshima, M. M. Salomaa, and K. Machida, Phys. Rev. A **68**, 023611 (2003); Y. Kawaguchi and T. Ohmi, Phys. Rev. A. **70**, 043610 (2004).

[2]R. Rossignoli and A. M. Kowalski, Phys. Rev. A **72**, 032101 (2005).

[3]E. Fukuyama, M. Mine, M. Okumura, T. Sunaga and Y. Yamanaka, Phys. Rev. A **76**, 043608 (2007).

Controlled deflection of cold atomic clouds and of Bose-Einstein condensates

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We present a detailed, realistic proposal and analysis of the implementation of a cold atom deflector using time-dependent far off-resonance optical guides. An analytical model and numerical simulations are used to illustrate its characteristics when applied to both non-degenerate atomic ensembles and to Bose-Einstein condensates. Following a previous study of a cold atom beam splitter[1], we show that it is possible to deflect almost entirely an ensemble of ^{87}Rb atoms falling in the gravity field using for all relevant parameters values that are achieved with present technology[2]. We discuss the limits of the proposed setup, and illustrate its robustness against non-adiabatic transitions.

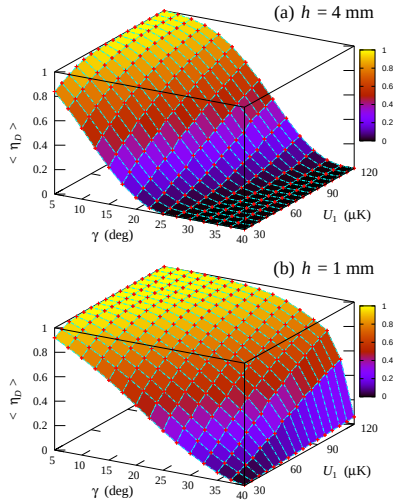

Figure 1: *Total deflection probability* $< \eta_D >$ *of an atomic cloud of* ^{87}*Rb of size* $\sigma_0 = 0.155$*mm at tempurature* $T = 10\mu$*K, as a function of the deflection angle* γ *and the depth of the oblique guide potential* U_1 .

[1]N. Gaaloul, A. Suzor-Weiner, L. Pruvost, M. Telmini and E. Charron, Phys. Rev. A 74 023620 (2006)
[2]N. Gaaloul, A. Jaouadi, L. Pruvost, M. Telmini and E. Charron, submitted to Phys. Rev. A (2008)

Equilibrium phases of a dipolar spinor Bose gas

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[1]*University of California, Berkeley, USA*

A wide range of correlated materials exhibit spatially inhomogenous phases due to the influence of competing interactions. For instance, in classically ordered systems such as magnetic thin films, the short-range ferromagnetic interaction is frustrated by the spatially anisotropic, long-ranged dipolar interaction. This results in spatially modulated phases exhibiting a wide range of morphologies. Despite the ubiquity of materials that exhibit competing interactions, there remain a range of open questions regarding the properties of such frustrated magnetic systems. Of particular interest in this regard are quantum fluids in which frustrated magnetic order is juxtaposed with superfluidity.

Here, we investigate the properties of quasi two-dimensional $F = 1$ spinor Bose gases of ^{87}Rb under the competing influences of a long-range dipolar interaction and a short-range ferromagnetic interaction. Due to this competition, we observe the spontaneous formation of modulated spin domains that exhibit crystalline order. This self-organized phase is seen both as resulting from a dynamical instability in a transversely magnetized condensate as well as in equilibrium resulting from a gradual cooling of thermal spinor gases. The fact that this crystalline structure is observed under a wide range of initial conditions indicates that this ordered phase could represent an equilibrium configuration of this dipolar quantum fluid.

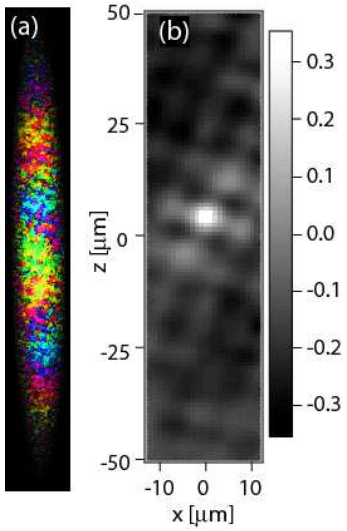

Figure 1: *(a) Spin textures in a spontaneously modulation spinor condensate. The amplitude (orientation) of magnetization is represented by the brightness (hue). (b) The spin correlation function of the dipolar spinor condensate indicates spin domain structures that exhibit crysalline order with a modulation period of around 10 μm.*

Fractional Quantum Hall Physics with Rotating Few-Body Bose Clusters

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A hallmark behavior of low-dimensional, interacting and quantum-degenerate gases is their potential to be mapped onto systems of particles with a statistical character which differs from the constituent particles. In one dimension, this takes the form of the recently observed Tonks-Girardaeu gas[1], where bosons effectively behave as a fermionic gas. In two dimensions the behavior is richer, including the possibility to observe fractional statistics, as occurs in the fractional quantum Hall effect for a two-dimensional electron gas in strong magnetic field. An analogous situation can occur for a rotating and harmonically trapped interacting Bose gas[2] when the total angular momentum of the gas approaches the square of the number of constituent particles. Previous experiments with large rotating superfluid gases[3] have obtained and studied the classical dynamics of large numbers of superfluid vortices, but fall short of the fractional quantum Hall limit. Here we report experiments which attempt to circumvent the technical difficulty of these experiments by working with small numbers of atoms, and attempt to probe the strong particle correlations expected in the fractional quantum Hall regime. We investigate quantum-degenerate few-body clusters of ^{87}Rb atoms confined to an optical lattice potential with locally rotating on-site potentials and repulsive interactions. In the centrifugal limit, when the microtrap rotation frequency differs from its vibration frequency by an amount comparable to the interaction energy, a large scale degeneracy is expected to be broken by particle interactions, and strong atomic correlation is expected in the few-particle ground states. We have designed and implemented an adiabatic pathway for populating these correlated ground states by controlling the rate and amplitude of a rotating deformation to the on-site potential of an optical lattice, similar to the mathod proposed by Popp et al.[4]. We probe short range correlations and momentum distributions by a combination of photoassociation loss and time-of-flight imaging, and compare to expectations from exact numeric evolution of the few-body system with no free parameters. We investigate the role of anharmonic terms in the local trap potential, and their effect on adiabatic pathways to FQH ground states.

[1]Kinoshita, T., T. Wenger, et al. (2004) Science 305(5687): 1125-1128,
Paredes, B., A. Widera, et al. (2004) Nature 429(6989): 277-281
[2]Cooper, N. R. and N. K. Wilkin (1999) Phys Rev B 60(24): R16279-82
[3]Schweikhard, V., I. Coddington, et al. (2004) Phys Rev Lett 92(4): 040404-4
[4]Popp, M., B. Paredes, et al. (2004) Phys Rev A 70(5 B): 053612-6

A pumped atom laser

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Although the peak flux in atom lasers realised to date is competitive with thermal beams, the duty cycle is low, giving a lower average flux[1] [2] [3]. We aim to produce a continuous atom laser with a squeezed output for fundamental studies and applications. In this poster, we present the realisation of a pumped atom laser. In our experiment, atoms are transferred by an irreversible Bose enhanced process from a source condensate to the target condensate that is the lasing mode. While the lasing mode is being pumped by the source, atoms are also output-coupled to form a freely propagating atom laser beam. This process runs continuously for 200ms. We test our results against a rate equation model[4]. This is a necessary step towards the production of a truly continuous atom laser. There appear to be two pumping mechanisms that we can access in the experiment. One is related to Raman super-radiance[5] [6]. The other is related to a STIRAP process. In order to elucidate the pumping mechanism we have also performed experiments in a short (100μs) pulsed regime. We have investigated both on and off resonant pumping of the lasing mode in this short pulse system.
In future work, we will combine this experiment with an atom delivery system to replenish the source.

[1] N. P. Robins et al, PRL 96, 140403 (2006).
[2] W. Guerin et al, PRL 97, 200402 (2006).
[3] A Öttl et al, PRL 95, 090404 (2005).
[4] N. P. Robins et al, arXiv:0711.4418.
[5] D. Schneble et al, PRA 69, 041601 R (2004).
[6] Y. Yoshikawa et al, PRA 69, 041603 R (2004).

Tailoring Motional States of Strongly Interacting 2D Bose-Einstein Condensates: Creation of Vortices and Antivortices

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We have previously proposed a tailoring method which enables us to move the populations of motional quantum states to another in an efficient way[1]. It is based on time-dependent double-well potentials and one-component description. It can be generalized, so that it can be successfully applied to strongly interacting 1D Bose-Einstein condensates. However, in the case of strongly interacting Bose-Einstein condensates there is a significant difference between 1D and 2D systems.

At the moment, we are studying various 2D variations of the previous method and the consequences of dimensionality. As an example, we have studied a ring shaped geometry, which consists of two harmonic ring traps. That is, we have two harmonic traps, which depend only on radial co-ordinate, within each other. The cross-section of this system reveals the double-well structure. As a result of the tailoring process, we seem to get similar results for a moment compared to 1D system. However, these states are not stable. The situation is similar compared to 2D solitons decaying into vortices and antivortices. This phenomenon is often called snake-instability.

The second geometry we are considering consists of two cylindrically symmetric harmonic traps. The line connecting the bottoms of the wells can be considered as a special direction. The cross-section in that direction shows the double-well structure. However, unlike in the ring trap case, here we have a preferred direction. One, can ask whether it is possible to gain angular momentum during the tailoring process. By changing the preferred direction during the process one might be able to do that.

[1] K.Härkönen, O.Kärki and K.-A. Suominen, Phys.Rev. A **74**, 043404 (2006)

A dual-species BEC with tunable interactions

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[2] *Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, CA 91125, USA*
[3] *University of British Columbia, Vancouver, BC V6T 1Z1, CANADA*

Dual-species quantum gases are currently a subject of significant interest for realizing dipolar interactions between ultracold molecules and probing Efimov quantum states. Understanding how the spatial overlap of the two species changes with interatomic interactions will be important for future experiments.[1] We will report on the observation of controllable phase separation in a dual-species Bose-Einstein condensate with ^{85}Rb and ^{87}Rb.[2] Interatomic interactions of the different components determine the miscibility of the two quantum fluids. In our experiments, we can clearly observe immiscible behavior via a dramatic spatial separation of the two species (Fig. 1). Furthermore a magnetic-field Feshbach resonance is used to change them between miscible and immiscible by tuning the ^{85}Rb scattering length. The spatial density pattern of the immiscible quantum fluids exhibits complex alternating-domain structures that are uncharacteristic of its stationary ground state.

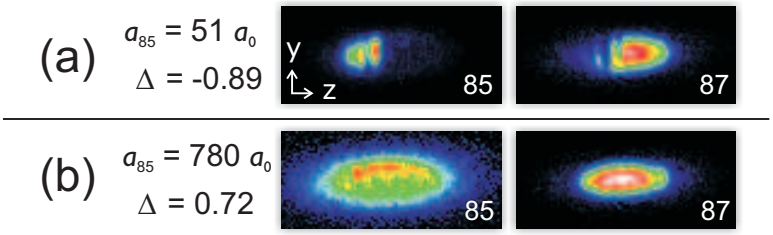

Figure 1: *Absorption images of (a) a phase separated and (b) a miscible mixture of ^{85}Rb and ^{87}Rb. The long direction of all the images represents the position space distribution. The parameter* $\Delta = \frac{a_{85}\,a_{87}}{a_{85-87}^2} - 1$ *characterizes the tendency of the two clouds to phase separate; the clouds are expected to be immiscible with* $\Delta < 0$*. The optical depth of the lower ^{85}Rb image has been scaled by a factor of five for clarity.*

[1] S. B. Papp and C. E. Wieman, "Observation of heteronuclear Feshbach molecules from a ^{85}Rb^{87}Rb gas", Phys. Rev. Lett. 97, 180404 (2006).

[2] S. B. Papp, J. M. Pino, and C. E. Wieman, "Studying a dual-species BEC with tunable interactions", arXiv:0802.2591 (2008).

Mind the gap in Raman scattering of a Bose gas !

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We explore the finite temperature many body physics through the Raman transition between two hyperfine levels of a Bose condensed atom gas. Unlike the Bragg scattering where the phonon-like nature of the collective excitations has been observed[1], a different branch of thermal atom excitation is found theoretically in the Raman scattering[2] . This excitation is predicted in the generalized random phase approximation and has the parabolic dispersion relation $\epsilon_{1,\mathbf{k}} = \epsilon_g + \mathbf{k}^2/2m$. The gap $\epsilon_g = gn$ results from the exchange interaction energy with the other atoms. During the Raman transition, the transferred atoms become distinguishable from the others and release this gap energy. The scattering rate is determined as a function of the transition frequency ω and the transferred momentum $\mathbf{q}$ and show the corresponding resonance around this gap (see Fig. 1).
Nevertheless, the Raman scattering process is attenuated by the superfluid part of the gas. The macroscopic wave function of the condensate deforms its shape in order to screen locally the external potential displayed by the Raman light beams. This screening is total for a condensed atom transition in order to prevent the condensate to scatter incoherently[2]. The experimental observation of this result would explain some of the reasons for which a superfluid condensate moves coherently without any friction with its surrounding.

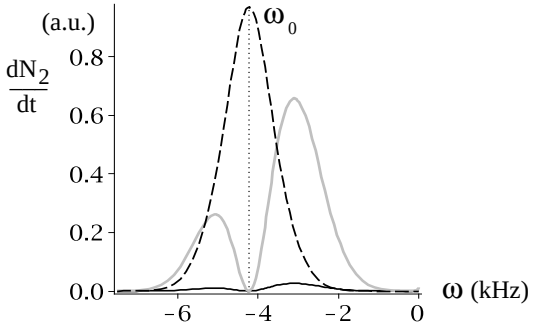

Figure 1: *Scattering rate of a bulk Bose condensed gas of* ^{87}Rb *for* $\mathbf{q}^2/2m = 30$Hz. *The black dashed/solid curve is the rate calculated in absence/presence of the screening. See the grey curve for a magnification of the black solid curve (*$\times 25$*). The superfluid fraction is 80% and* $\epsilon_g = 4.3$kHz. *In this process, atoms with an initial momentum* $\mathbf{k}$ *and energy* $\epsilon_{1,\mathbf{k}} = \epsilon_g + \mathbf{k}^2/2m$ *are transferred into a second level with momentum* $\mathbf{k}+\mathbf{q}$ *and energy* $\epsilon_{2,\mathbf{k}+\mathbf{q}} = (\mathbf{k}+\mathbf{q})^2/2m$ *provided* $\omega = \epsilon_{2,\mathbf{k}+\mathbf{q}} - \epsilon_{1,\mathbf{k}}$. *In absence of screening, a resonance appears at* $\omega_0 = \mathbf{q}^2/2m - \epsilon_g$. *The screening effect strongly reduces the Raman scattering and, in particular, forbids it for condensed atoms i.e. for* $\omega = \omega_0$.

[1] D.M. Stamper-Kurn et al., Phys. Rev. Lett. **83**, 2876 (1999).
[2] P. Navez, Physica A **387**, 4070 (2008); P. Navez, Physica A **356**, 241-278 (2005).

Feshbach Resonances in Bose-Fermi Cr Gas Mixtures

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We report calculations of Feshbach resonances in ultra-cold boson-fermion Cr samples in an optical trap. For the ^{52}Cr-^{53}Cr and ^{53}Cr-^{53}Cr systems, the Feshbach resonances are driven by magnetic dipolar interaction in the ground state with a large magnetic moment, $6\mu_B$, and hyperfine interaction of strength $a_{\rm hf} = -83.6$ MHz. The formation of an extended class of magnetically tuned Feshbach resonances is predicted for both boson-fermion, boson-boson and fermion-fermion mixtures. The positions and widths of the resonances are determined from a full-scale coupled channel calculation, incorporating the dipole-dipole interaction, whose solutions are analytically extended using the quantum defect method for the $1/R^6$ potential[1]. The resulting scattering matrix is transformed[2] into the hyperfine representation and resonance information is extracted. The coupled channel bound state calculations are employed to monitor the progression of bound states into resonances as a function of applied magnetic field, also used for identification.

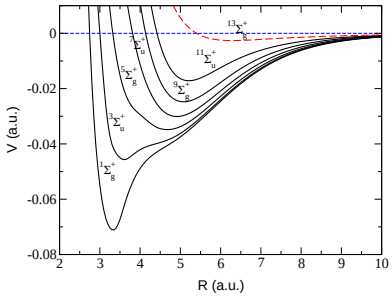

Figure 1: *Ab initio* Cr_2 Born-Oppenheimer potentials[3]

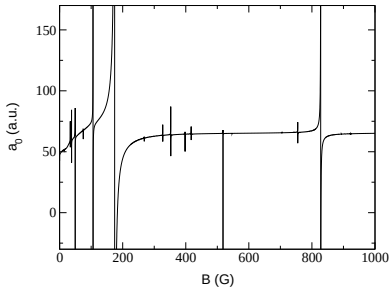

Figure 2: Calculated ^{52}Cr-^{53}Cr scattering length as a function of magnetic field (preliminary data)

[1]Bo Gao, Phys. Rev. A **58**, 1728 (1998)
[2]Bo Gao *et al.*, Phys. Rev. A **72**, 042719 (2005)
[3]Z. Pavlović *et al.*, Phys. Rev. A **69**, 030701 (2004)

Hydrodynamic excitations in a Bose-Einstein condensate

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In our BEC of sodium atoms we have reached a record number of 250 million condensed atoms in a highly asymmetric potential of 96×1.5 Hz. This allows us to study the hydrodynamic regime. We define the hydrodynamicity as the ratio between the collision rate $\gamma_{\rm col}$ and the axial trap frequency $\omega_{\rm ax}$. In our experiment the hydrodynamicity is more than 10, which allows us to study the propagation of both first and second sound in the two-fluid model. As an initial step we have studied the out-of-phase oscillation of the condensate with respect to the thermal cloud, which is reminiscent to second sound in the case of liquid helium. If we consider the condensate as a superfluid, which flows through any obstacle without friction, one expects this motion to be undamped. By displacing the condensate with a shallow dipole trap with the respect to the thermal cloud, we have observed this out-of-phase oscillation. The frequency of the motion is shifted with respect to the trap frequency and most importantly becomes damped (see Fig. 1). We have measured the shift and damping under various experimental conditions. We observe a decrease of the damping for decreasing axial trap frequencies, which suggests that the damping will vanish in the uniform case. We will discuss the origin of the damping mechanism at the conference.

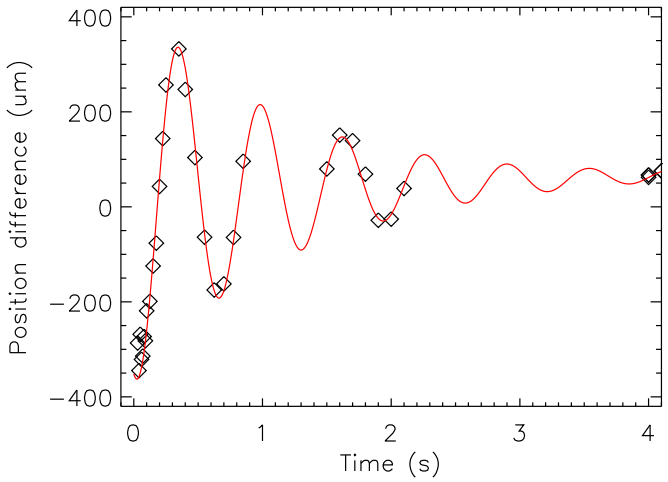

Figure 1: *Out-of-phase oscillation of the condensate with respect to the thermal cloud.*

Atom Interferometry with Interacting Bose-Einstein Condensates

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Recent experiments[1] have demonstrated that the relative phase Δ of two elongated Bose-Einstein condensates (BECs) can be inferred by merging them on an atom chip. This is done by monitoring the expanded combined cloud, which becomes broader as Δ approaches π. We show that this effect is due to the resonant production of a soliton, and its subsequent decay into vortices[2] (see Fig. 1). We tailor the performance of the interferometer by varying the merging time τ and temperature. Increasing the temperature broadens the resonance so that vortices are generated over a wider range of Δ. By characterising the function of the interferometer we identify the advantages of using interacting BECs, and discuss their potential applications as motion detectors and sensors of weak forces.

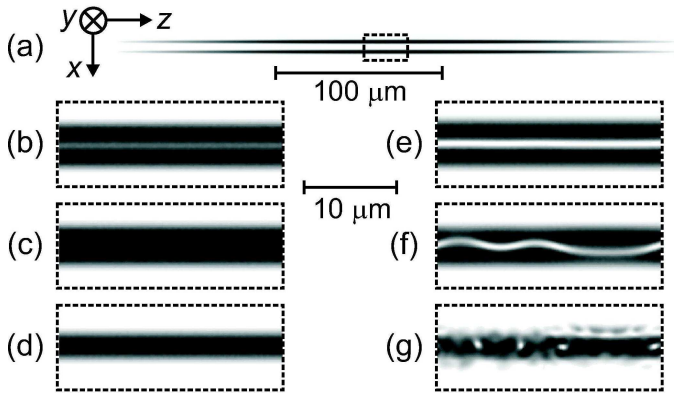

Figure 1: *(a) Atom density profile of the two BECs in the $y = 0$ plane (axes inset) at $t = 0$. (b)-(g) Density profiles within the region enclosed by the dashed rectangle in (a) at key stages of the merging process ($\tau = 5ms$) calculated for $\Delta = 0$ at $t = 3$ ms (b), 4 ms (c), 5 ms (d), and for $\Delta = \pi$ at $t = 3$ ms (e), 4 ms (f), and 5 ms (g). Upper [lower] horizontal bars show scales in (a) [(b)-(g)].*

[1] G.-B. Jo, J.-H. Choi, C. Christensen, T. Pasquini, Y.-R. Lee, W. Ketterle and D. Pritchard, Phys. Rev. Lett. **98** 180401 (2007)

[2] R.G. Scott, T.E. Judd and T.M. Fromhold, Phys. Rev. Lett. **100** 100402 (2008)

Virial expansion for ultracold trapped fluids and the exactness of the local density approximation

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We derive the virial expansion of the grand potential for a fluid confined by an external field. The fluid may be classical or quantum and it is assumed that interatomic interactions are pairwise additive. We analyze several confining potentials and we find the appropriate "generalized" volume and pressure variables for each case that replace the usual volume and hydrostatic pressure. We emphasize that this treatment yields the correct equation of state of the fluid. As a corollary, we show that the so-called *local density approximation* is exact for these systems in the thermodynamic limit. We discuss the relevance of these findings in the description of the currently confined ultracold gases. We present explicit results for an ultracold gas confined by a quadrupolar potential within the Hartree-Fock approximation.

Dynamical evolution of an interacting Bose gas at low temperatures described through a quantum kinetic equation

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We study an interacting Bose gas at low temperatures confined in a harmonic potential in three dimensions. The system under study consists of N particles out of equilibrium distributed on the first κ energy levels of the ideal harmonic oscillator. By numerically solving the time-dependent Schrödinger equation for a few number of particles we first demonstrate that the system reaches thermal equilibrium through ellastic binary collisions. Then, based on a Boltzmann scheme, we derive the quantum kinetic equation that leads the system towards thermal equilibrium when pair interactions between particles are considered. We find that the system obeys two quantum kinetic equations for the occupation numbers n_κ, one for negative values of the chemical potential ($\mu < 0$) and other for the chemical potential equal to zero ($\mu = 0$). We also find that the kinetic equations satisfy total energy conservation for the N particles, and that it has as a stationary solution the Bose-Eisntein distribution. By numerically solving the coupled system of equations for each case ($\mu < 0$ and $\mu = 0$), we determine the evolution in time of the occupation number n_κ for each state.

Evolution and Measurement of Relative Phase in a Two-Component Bose-Einstein Condensate

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Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

Knowledge of the phase of matter waves is of crucial importance for studies of interferometry, entanglement and precision measurement. We are studying the spatio-temporal evolution of the relative phase in a two-component Bose-Einstein condensate: the $|F = 1, m_F = -1\rangle$, $|F = 2, m_F = +1\rangle$ pseudo-spinor system of ^{87}Rb, using a micromagnetic trap on an atom chip. In addition to previous studies of phase measurement for two-component systems of cold thermal atoms[1], we are investigating two techniques involving (i) phase reconstruction using a spatially sensitive interferometric technique, and (ii) phase retrieval using a non-interofometric algorithm[2]. We prepare condensates in a superposition of the two spin states using a two-photon microwave-radiofrequency pulse of duration $\sim 1\,\mathrm{ms}$, and allow the system to evolve via nonequilibrium mean field dynamics for hundreds of milliseconds. We then observe the amplitude of each component by measuring the population of each spin state, with or without the addition of a second two-photon pulse (Ramsey technique). Our preliminary results show evolution of the relative phase along the direction of weak confinement (Fig. 1), consistent with mean field modelling. This work is important in the context of quantum technologies such as collisional phase gates for quantum information processing[3], and atomic clocks using trapped ultracold atoms. The role of mean field dynamics, phase diffusion and decoherence in these applications is yet to have detailed experimental investigation.

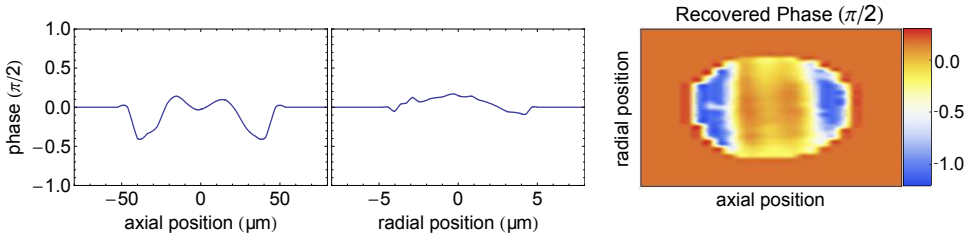

Figure 1: *Reconstructed relative phase of a two-component Bose-Einstein condensate after 90 ms of nonequilibrium mean field dynamics using an interferometric method.*

[1] J.M. McGuirk *et. al.*, Phys. Rev. Lett. **89**, 090402 (2002).
[2] Y.E. Tan *et. al.*, Phys. Rev. E **68**, 066602 (2003).
[3] P. Treutlein *et. al.*, Phys. Rev. A **74**, 022312 (2006).

Inelastic collision dynamics of ^{87}Rb spin-2 Bose-Einstein Condensates

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We have experimentally investigated the dynamics of ^{87}Rb spin-2 Bose-Einstein condensates confined in an optical trap. Owing to its rich variety of internal degrees of freedom, many interesting dynamics can be observed. As well as elastic spin-exchange collisions, ^{87}Rb spin-2 condensates in the upper hyperfine level have large inelastic collision rates in comparison with those of lower hyperfine levels because of hyperfine-changing collisions[1,2]. Previously, the inelastic collision rates were roughly estimated under the condition in which spin-exchange collisions occurred, and only the loss rates of total number of atoms were estimated. It is primarily important to manifest mechanisms of inelastic collisions individually for each magnetic sublevel for the study of spin dynamics in multi-component condensates.

In this work, we have observed the time dependence of spin populations in spin-2 two-component condensates initially populated in several spin-states at 3 G of the magnetic field in which the spin-exchange collisions between different magnetic sublevels in the same hyperfine states were suppressed. Figure 1 depicts time-dependence of number of condensed atoms initially populated in (a) $m_F = -1$ and $m_F = -2$ states, and (b) $m_F = +1$ and $m_F = -2$ states with almost equal populations. We have also observed those of other spin-states; $m_F = 0$ and $m_F = -2$ states, $m_F = +2$ and $m_F = -2$ states, and $m_F = +1$ and $m_F = -1$ states. The results show that the inelastic collision rates depend on spin-states. The spin-dependent inelastic collision rates can be explained by corresponding collision channels[3].

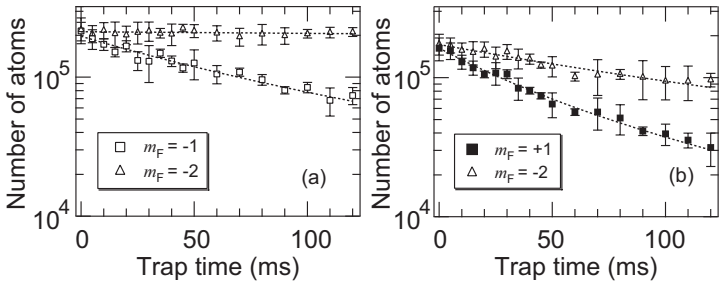

Figure 1: *Time-dependence of condensed atoms initially populated in $m_F = -1$ and $m_F = -2$ (a), and $m_F = +1$ and $m_F = -2$ (b).*

[1] T. Kuwamoto *et. al.*, Phys. Rev. A 69, 063604 (2004).
[2] H. Schmaljohann *et. al.*, Phys. Rev. Lett. 92, 040402 (2004).
[3] Y. Kawaguchi, H. Saito, and M. Ueda (private communication).

Optical Traps for ultracold metastable helium atoms

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One of the main characteristics of metastable helium atoms is their high internal energy (20 eV). This energy can be released when a metastable atom hits a surface, ejecting one electron. Therefore, using a Channeltron Electron Multiplier (CEM), one can detect atoms with a time resolution of up to 5 ns. However, this high internal energy raises the problem of inelastic Penning ionizations, following: $He^* + He^* \rightarrow He + He^+ + e^-$.
This process has a rate of the order of 10^{-10}cm^3.s^{-1} but is reduced by four orders of magnitude if the atoms are spin polarized due to total spin conservation.
We report on the progess of the set up of a dipole trap for ultracold metastable helium using a red detuned fiber laser at 1560nm. One of the aims of this optical trap is to release the constraint on the magnetic field value. We plan to measure the magnetic field dependance of inelastic collision rates initially calculated by P. O. Fedichev[1], for temperatures smaller than 10μK. In a spin polarized gas of helium, the spin-spin interaction produces spin relaxation (α_{rel}) and relaxation induced Penning ionization (α_i) if the polarization condition is no longer maintained.
We also present the development of a new generation of magnetic trap based on a clover leaf trap setup which is compatible with in situ loading of a condensed gas into a 3D optical lattice[2]. The coil geometry is designed to optimize optical access on 8 independant optical axes. We intend to monitor the Penning ionization rate in order to follow the real-time dynamics of the Superfluid-Mott insulator quantum phase transition.

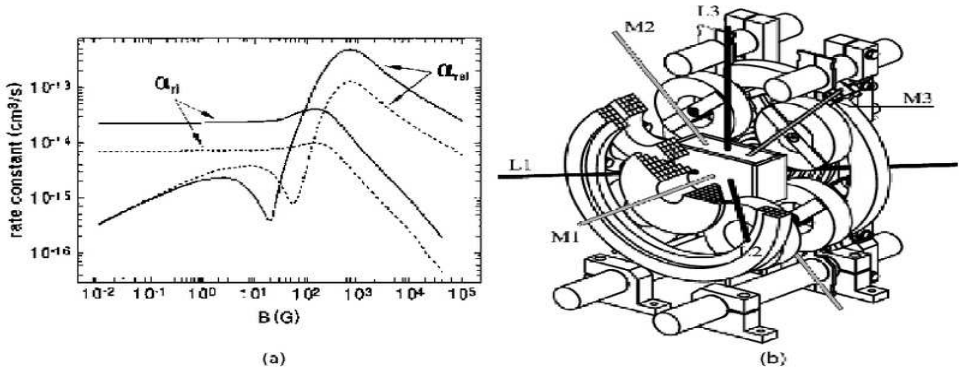

Figure 1: *(a) Rate constants α_{rel} and α_i. (b) Setup of the new magnetic trap.*

[1] P. O. Fedichev, M. W. Reynolds, U. M. Rahmanov and G. V. Shlyapnikov, *Phys. Rev. A* **53** 1447 (1996)
[2] C. Buggle, N. Zahzam, J. Dugué and M. Leduc, in preparation

Weightless Bose-Einstein Condensates

Y. P. Singh[1], T. van Zoest[1], W. Herr[1], N. Gaaloul[1], S. Seidel[1], E. M. Rasel[1], W. Ertmer[1], K. Bongs[2], T. Könemann[3], H. Müntinga[3], W. Brinkmann[3], C. Lämmerzahl[3], H. Dittus[3], E. Kajari[4], R. Walser[4], W. P. Schleich[4], A. Vogel[5], K. Sengstock[5], W. Lewoczko-Adamczyk[6], M. Schiemangk[6], A. Peters[6], T. Steinmetz[7], J. Reichel[7]

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[2]*Midlands Ultracold Atom Research Centre, Birmingham B15 2TT, United Kingdom*
[3]*ZARM, University of Bremen, 28359 Bremen, Germany*
[4]*University of Ulm, Institute for Quantum Physics, 89081 Ulm, Germany*
[5]*University of Hamburg, Institute for Laser-Physics, 22761 Hamburg, Germany*
[6]*Institute for Physics, Humboldt University of Berlin, Germany*
[7]*Laboratoire Kastler Brossel de l'E.N.S. 75231 Paris, France*

Realization of a Bose-Einstein Condensate (BEC) in the year of 1995 has opened up a plethora of new possibilities to understand the fundamental questions such as quantum phase transitions, super fluidity, matter wave interference etc. The extremely low energy scales achieved in a typical earth-bound laboratory BEC has motivated us to continue the path towards lower energy scales by lifting Earth-bound laboratory restrictions. In particular microgravity offers several advantages for the fundamental research on cold quantum gases. First of all, it can provide an unperturbed evolution for long durations which is crucial for atom interferometers and atomic clocks. In a microgravity environment, the precision of these sensors can be extended by upto three orders of magnitude. Second it provides mass independent confining potential which is very important for the research on a mixture of quantum gases such as degenerate Fermi gases. Another important point is that in a microgravity environment, it is possible to adiabatically lower the trapping potential resulting in ultra-large condensates. The effect of ultra-weak long range forces become important in these condensates, which is expected to lead to new kinds of low energy phase transitions. More over it is possible to manipulate ultra-large condensates with a very high spatial resolution. In addition, microgravity is a prerequisite for fundamental tests in the quantum domain such as the equivalence principle or the realisation of ideal reference systems. A miniaturized and remote controlled facility to study BECs in the extended free fall at the drop tower in Bremen and during parabolic flights has been realized. The facility permits us to study the generation and outcoupling of BECs in microgravity, the study of decoherence and atom interferometry. For the first time, we report on the realization of Rb^{87} BECs and its subsequent evolution for as long as 1 second in a microgravity environment.

State selective single atom detection on a magnetic microchip

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The possibility to detect small amounts of atoms on a magnetic microchip opens the door to a variety of interesting fundamental experiments in the field of ultracold quantum gases. Standard absorption imaging requires a minimum number of several hundred atoms. Thus novel detection methods with single atom sensitivity are currently developed.
Here, we present a single atom detector which is implemented in our magnetic microchip setup. The detection scheme is based on optical ionization of single atoms and subsequent counting of the ions in a channeltron. With this method a detection efficiency of 60% was achieved. We characterized the detector by ionizing a cloud of rubidium atoms at a temperature of about 10 μK in different combinations of magnetic and optical dipole traps on the microchip and with varying excitation laser power.
Furthermore we were able to record in situ a complete hyperfine resolved two photon transition spectrum of a single cloud (see fig.1). It was also possible to selectively detect single atoms in different hyperfine groundstates. By additionally irradiating microwaves, the atoms could be ionized depending on their position within the magnetic trap according to their temperature. In that way the temperature distribution of the atoms in the magnetic trap could be determined.

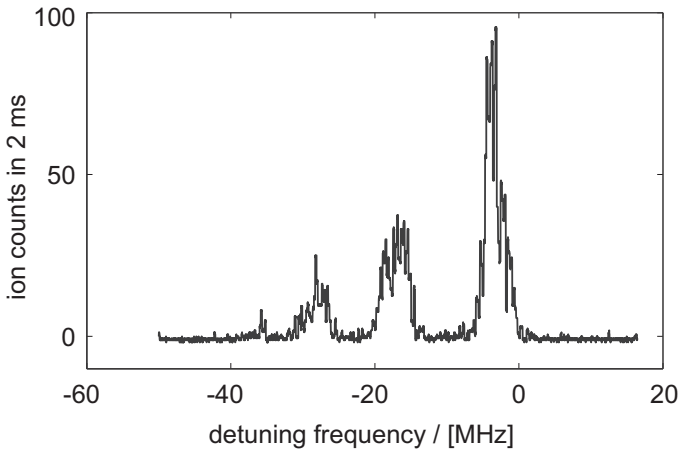

Figure 1: *Two photon transition between the 5 $S_{1/2}$, $F = 2$, and the four hyperfine levels 5 $D_{5/2}$, $F = 4...1$, recorded by state selective single atom laser ionization of a single ultracold cloud on an atom chip. The spectrum is scanned by detuning the frequency of the excitation laser.*

Bosonic Tonks-Girardeau Gases in a Split Trap

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One-dimensional quantum gases in the strong correlation limit are interesting from an experimental as well as from a theoretical point. Apart from opening new avenues of exploration in physics, they are also highly amenable to theoretical treatment, allowing for detailed insight into many-particle physics.

In our work we have calculated the exact many-body properties of a bosonic Tonks-Girardeau gas confined in a harmonic potential with a tunable δ-function barrier at the trap center. This system is one of the few non-trivial examples where a mathematically exact solution for the density matrix can be found and from which, in turn, many interesting physical properties can be derived.

Here we show the dependence of the density, the pair distribution function, the momentum distribution, and the coherence as a function of barrier height for samples of up to 50 particles. We find, through diagonalization of the reduced single particle density matrix, that with increasing barrier height the coherence of the sample becomes an oscillating function of the particle number. This odd-even effect is shown to also manifest itself in both the momentum distribution and the visibility of the interference fringes at the end of free temporal evolution. Finally, we present an investigation into the entanglement inherent in split Tonks gas samples.

Vortex nucleation and non-equilibrium dynamics in a Bose-Einstein condensate at finite temperatures

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Vortex nucleation and lattice formation in a rotationally stirred atomic Bose-Einstein condensate is intimately connected to the thermal behaviour of the Bose field[1,2,3], and thus provides an important testbed for dynamical theories of cold bosonic gases. A typical experiment[4] involves stirring a very cold condensate with an elliptically deformed rotating trap. Angular momentum, in the form of quantized vortices, is imparted to the condensate through its coupling to the non-condensed fraction. A non-condensed fraction may be formed by the excitation of dynamically unstable collective excitations of the condensate, leading to a highly excited state, far from equilibrium. The subsequent dissipative relaxation to an equilibrium state thus requires an analysis beyond a mean-field description, as recognised by a number of authors (e.g. [3]).

Here we present a model of vortex nucleation in a quasi-2D condensate initially at $T = 0$ and perturbed by a weakly anisotropic rotating trapping potential. In our approach the low energy dynamics of the Bose field are described using a classical field method in which the atom number and (rotating-frame) energy are conserved[5]. Our approach allows us to quantify the development of the thermal component, and determine its role in vortex nucleation and dynamics, during a strongly non-equilibrium process. We discuss methods of temporal analysis we have developed to characterise the field and identify the condensate in the presence of an irregular distribution of vortices, where traditional definitions[6] of Bose-condensation do not describe a single well-defined condensate mode. We show that turbulent superfluidic behaviour can be distinguished from thermal behaviour by analysing temporal correlations of the field. We also determine the thermodynamic parameters of the thermal component, and extract rates of excitation damping from the classical field trajectories.

[1] S. Sinha et al., Phys. Rev. Lett. **87**, 190402 (2001).
[2] C. Lobo et al., Phys. Rev. Lett. **92**, 020403 (2004).
[3] K. Kasamatsu et al., Phys. Rev. A **67**, 033610 (2003).
[4] K. W. Madison et al., Phys. Rev. Lett. **84**, 806 (2000); E. Hodby et al., Phys. Rev. Lett. **88**, 010405 (2001); J. R. Abo-Shaeer et al., Science **292**, 476 (2001).
[5] A. S. Bradley et al., Phys. Rev. A **77**, 033616 (2008).
[6] O. Penrose et al., Phys. Rev. **104**, 576 (1956).

Quantum Fluctuation Effect in Dynamical Instability of Bose–Einstein Condensate with a Highly Quantized Vortex

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The Bose–Einstein condensation, which occurs in many-body quantum system, should ultimately be treated by the quantum field theory. There the quantum fields, describing quantum fluctuation, are usually expanded in terms of an appropriate complete set of wave functions corresponding to a quasi-particle picture. The Bogoliubov-de Gennes (BdG) equations whose eigenfunctions form such a complete set, are used for a number of theoretical works on the trapped Bose-Einstein condensates[1], and are known to give the energies of the quasi-particles when all the eigenvalues are real. The BdG equations can have complex eigenvalues in general, and the existence of complex modes is associated with the dynamical instability, that is, the decay of the initial configuration of the condensate[1]. In our previous work[2] we have developed a consistent formulation of the quantum field theory in the presence of complex eigenvalues of the BdG equations. We have given the complete set including complex modes and expanded the quantum field. It is then shown that the state space is an indefinite metric one and that the free Hamiltonian is not diagonalizable in the conventional bosonic representation. However, it is not clear yet how one should select quantum states (called physical states), reflecting the instability of the condensate. In order to study the instability, we have formulated the linear response of the density against the time-dependent external perturbation within the regime of Kubo's linear response theory. In this work, we examine several candidates of quantum states for a system with a highly quantized vortex. We find suitable physical states by numerical calculations, implying that they lead to the positive-definite fluctuation density and the time evolution of the density fluctuation representing the splitting from a highly quantized vortex to single vortices properly.

[1]L. Pitaevskii and S. Stringari, *Bose-Einstein Condensation*(Oxford University Press, New York, 2003).
[2]M. Mine, M. Okumura, T. Sunaga and Y. Yamanaka, Ann. Phys. **322**, 2327 (2007).

Rydberg excitation of a Bose–Einstein condensate

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Rydberg atoms provide a wide range of possibilities to tailor interactions in a quantum gas. Here we report on Rydberg excitation of Bose-Einstein condensed ^{87}Rb atoms. The Rydberg fraction was investigated for various excitation times and temperatures above and below the condensation temperature. The excitation is locally blocked by the van der Waals interaction between Rydberg atoms to a density-dependent limit. Therefore the abrupt change of the thermal atomic density distribution to the characteristic bimodal distribution upon condensation could be observed in the Rydberg fraction. The observed features are reproduced by a simulation based on local collective Rydberg excitations [1].

The excitation dynamics was investigated for a large range of densities and laser intensities and shows a full saturation and a strong suppression with respect to single atom behaviour. The observed scaling of the initial increase with density and laser intensity provides evidence for coherent collective excitation. This coherent collective behaviour, that was observed for up to several thousand atoms per blockade volume is generic for all mesoscopic systems which are able to carry only one single quantum of excitation [2].

Despite the strong interactions the evolution can still be reversed by a simple phase shift in the excitation laser field. We experimentally prove the coherence of the excitation in the strong blockade regime by applying an optical rotary echo technique to a sample of magnetically trapped ultracold atoms, analogous to a method known from nuclear magnetic resonance. We additionally measured the dephasing time due to the interaction between the Rydberg atoms [3].

[1] R. Heidemann, U. Raitzsch, V. Bendkowsky, B. Butscher, R. Löw, and T. Pfau
"Rydberg excitation of Bose-Einstein condensates"
Phys. Rev. Lett. **100** , 033601 (2008).

[2] R. Heidemann, U. Raitzsch, V. Bendkowsky, B. Butscher, R. Löw, L. Santos, T. Pfau
"Evidence for coherent collective Rydberg excitation in the strong blockade regime"
Phys. Rev. Lett. **99**, 163601 (2007).

[3] U. Raitzsch, V. Bendkowsky, R. Heidemann, B. Butscher, R. Löw, T. Pfau
"An echo experiment in a strongly interacting Rydberg gas"
Phys. Rev. Lett. **100** , 013002 (2008).

A high flux source of magnetically guided ultracold chromium atoms

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BEC production is typically performed by a time sequence of cooling steps leading to an average yield of 10^6 to $10^7 atoms/sec$ for the best alkali experiments and $10^3 atoms/sec$ for chromium BEC [1]. Considerable effort has been invested into the concept of a truly cw atom laser based on a magnetic guide which is loaded with ultracold atoms. The highest reported flux of magnetically guided alkali atoms approaches 7 $10^9 atoms/sec$ [2].
Due to the high magnetic moment, chromium atoms are particularly well suited for magnetic guiding. As the required magnetic field gradients are well compatible with gradients required for a magneto-optical trap (MOT) a moving molasses MOT can be installed in the guide for loading without mode matching problems. The MOT is fed by a Zeeman slower.
We observe a flux of up to 6 10^9 chromium atoms at a velocity of 6.2 m/sec. The velocity could be tuned by the frequency difference between the molasses beams between 2 and 20 m/sec. The guide was made of four current carrying wires separated by 4.6 cm leading to a magnetic gradient of 13 G/cm. Downstream the guided beam is radially compressed by reducing the wire distance to 9 mm and a gradient of 355 G/cm. In this area the flux and the temperature of the beam was measured by laser induced fluorescence. Radial and longitudinal temperatures were 1-2 mK in the compression zone. The beam will serve as an intense source of cold atoms to load an optical dipole trap (ODT) continuously. Future experiments are heading towards the demonstration of a high flux cw atom laser.

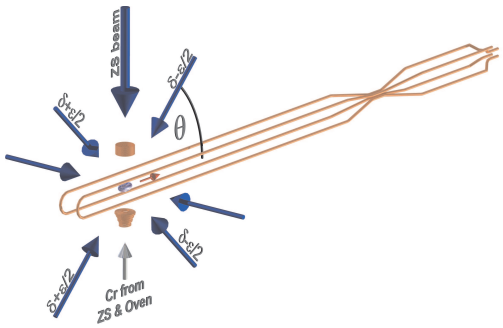

Figure 1: *Magnetic guide for ultracold chromium atoms. The total length of the guide is 1.4 m.*

[1] A. Griesmaier, J. Werner, S. Hensler, J. Stuhler and T. Pfau, Phys. Rev. Lett. **94**, 160401 (2005).
[2] T. Lahaye, J. M. Vogels, K. Guenter, Z. Wang, J. Dalibard, and D. Guéry-Odelin, Phys. Rev. Lett. **93**, 093003 (2004).

Controlled entanglement of spin and motional state of a Bose-Einstein condensate on a microwave atom chip

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We report on an experiment in which we use spin-dependent micropotentials to manipulate the quantum state of Bose-Einstein condensates (BECs) on an atom chip. The potentials are generated by a combination of static magnetic and microwave near-fields in the proximity of on-chip microwave guiding structures. Microwave dressing of hyperfine states allows us to adjust the spin-dependence of the potentials.[1]

We prepare a ^{87}Rb BEC in a superposition of the two internal spin states $|0\rangle \equiv |F = 1, m = -1\rangle$ and $|1\rangle \equiv |F = 2, m = 1\rangle$ and use the spin-dependent potentials to split and recombine the corresponding motional wave functions (see Fig. 1). Ramsey interferometry is used as a probe of the dynamics. The splitting process entangles the spin and motional quantum state of the atoms in a controlled way and leads to a collapse of the Ramsey interference contrast. After recombining the wave packets of the two spin states we observe a revival of the interference fringes, which shows that the manipulation is coherent.

The spin-dependent splitting process is a key ingredient for atom chip quantum gates, which rely on collisions in a spin-dependent potential to generate entanglement between atoms.[1,2] It could furthermore be used to study interaction-induced effects such as phase diffusion and entanglement in small BECs.

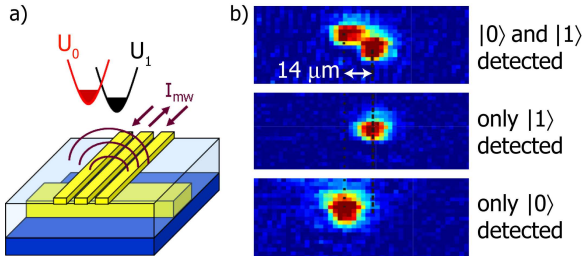

Figure 1: *Spin-dependent spatial splitting of a BEC with microwave near-field potentials. (a) Atom chip layout with microwave guiding structure. Potential U_i for internal state $|i\rangle$ $(i = 0, 1)$ is sketched. (b) Absorption images of BECs in a superposition of the spin states $|0\rangle$ and $|1\rangle$ after splitting the corresponding wave functions with the microwave potential. Top: both states are imaged. Center: only state $|1\rangle$ is imaged. Bottom: only state $|0\rangle$ is imaged.*

[1] P. Treutlein, T. W. Hänsch, J. Reichel, A. Negretti, M. A. Cirone, and T. Calarco, Phys. Rev. A **74**, 022312 (2006).

[2] P. Treutlein *et al.*, Fortschr. Phys. **54**, 702 (2006).

The splitting two-fluid hydrodinamic equations for Bose–Einstein condensate

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The subject of the consideration is the set of two-fluid hydrodinamic equations (see, for example[1,2])

$$\partial\rho/\partial t + \partial(\rho_s v_s + \rho_n v_n)/\partial x = 0, \quad \rho = \rho_s + \rho_n,$$

$$\partial(\rho_s v_s + \rho_n v_n)/\partial t + \partial(\rho_s v_s^2 + \rho_n v_n^2)/\partial x + \partial p/\partial x = 0,$$

$$\partial v_s/\partial t + \partial(v_s^2/2 + \mu)/\partial x = 0,$$

$$\partial S/\partial t + \partial(S v_n)/\partial x = 0,$$

where t is the time, x is the spatial coordinate, ρ is the density, S is the entropy per unit volume, $\rho_s \backslash \rho_n$ and $v_s \backslash v_n$ are the superfluid \ normal density and velosity respectively, μ is the chemical potential, p is the pressure.

We use these equations for the degenerate ideal Bose gas (see, for example,[3]). Then ρ_n is proportional to S. The equation of state is $p = BS^{5/3}$ (B — const). Ignoring at first the dependence of μ on $|v_s - v_n|$ according to the methodology[1], we obtain finally two splitting pairs of equations with respect to the variables v_n, S, and v_s, $R = (\rho - AS)$, where A is the constant

$$\partial v_n/\partial t + v_n \partial v_n/\partial x + (\partial p/\partial S)(S)^{-1}\partial S/\partial x = 0,$$

$$\partial S/\partial t + S\partial v_n/\partial x + v_n \partial S/\partial x = 0,$$

and

$$\partial v_s/\partial t + v_s \partial v_s/\partial x = 0,$$

$$\partial R/\partial t + R\partial v_s/\partial x + v_x \partial R/\partial x = 0.$$

The coupled equations are more complicated in general case when μ depends on the small value $|v_s - v_n|$.

The main results are unstable sharp peak density solutions of the initial value problems with respect to small perturbations and singular solutions of the Riemann problem by analogy to [4,5,6].

[1] I.M. Khalatnikov, "An introduction in the Theory of Superfluidity", W.A. Benjamin, New-York (1965).
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[4] V.I. Tsurkov, Comput. Math. Math. Phys., 11, 488 (1971).
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Effect of various time dependent longitudinal traps on Bose-Einstein condensate

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The temporal variation of non-linearity coefficient or the transverse trapping potential produces Faraday waves [1], which is recently observed [2] in a cigar-shaped Bose-Einstein condensate (BEC) involving Bogoliubov modes. In this work, we study the effect of various longitudinal trap variations in BEC. The solution of the Gross-Pitaevskii equation with time dependent parameters results a stationary Schrödinger eigen value equation, where the constant part of the potential acts as the eigen value [3]. A number of variations in the oscillator frequency can be analytically incorporated. We study both sinusoidal and transient variations of the longitudinal trap frequency on BEC profile. The transient variations include hyperbolic cotangent functions and delta kicks [4]. We observe amplification, spreading of the BEC profile and various center of mass motions, resulting coherent control of cigar-shaped BEC.

[1]M. Faraday, Philos. Trans. R. Soc. London **121**, 299 (1831)
[2]P. Engels, C. Atherton and M. A. Hoefer, Phys. Rev. Lett. **98**, 95301 (2007)
[3]R. Atre, P. K. Panigrahi and G. S. Agarwal, Phys. Rev. E **73**, 056611 (2006)
[4]S. S. Ranjani, Utpal Roy, P. K. Panigrahi and A. K. Kapoor, *cond-mat/0804.2881* (2008)

Noise and correlation measurements using single atom detection

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In this poster we will present the creation of correlations between the atoms scattered during the collision of two Bose-Einstein condensates of metastable helium atoms [1] . The detection of the atoms and the measurement of the second order correlation function is performed with a single atom 3D detector based on a micro-channel plate with a delay line anode. We show that atoms of opposite momenta (in the center of mass frame) as well as atoms of collinear momenta are correlated. The back to back correlation corresponds to the formation of atomic pairs and is a consequence of the elastic scattering of two atoms of initial well defined momenta. The collinear correlation is related to the bosonic bunching of randomly scattered atoms which is the Hanbury Brown Twiss effect. We show that in both cases the correlation lengths are related to the momentum distribution of the colliding condensates. The correlation functions we observe lend to a study of the violation of classical inequalities and of a reduction of atom number fluctuations.

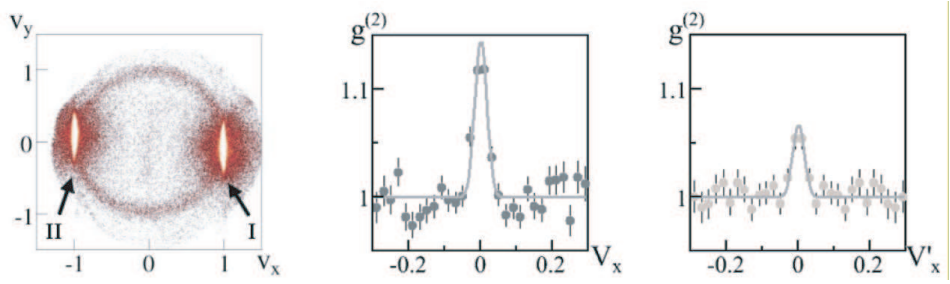

Figure 1: *a) Slice of the scattering sphere. The two colliding condensates (I and II) and the scattering shell are visible. b,c) Back to back and collinear correlation function along the long axis of the trapped condensate.*

[1]A. Perrin et al, "Atom-atom correlations in spontaneous four wave mixing of two colliding Bose-Einstein Condensates" Phys. Rev. Lett., Vol. 99, 150405, 2007.

Bose Condensates with Small s-wave Scattering Lengths: Effect of Dipolar Interaction

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Using a variational approach, we have calculated the *in-situ* size and time-of-flight (TOF) expansion of a cylindrically symmetric Bose-Einstein Condensate (BEC) when the s-wave scattering length (a_s) is close to zero (which can be realized via, for example, a Feshbach resonance). We have specifically investigated the effect of dipolar interactions when the magnetic moment of the atoms is nonzero, and examined the dependence of the dipolar effect on the number of atoms, trap geometry and a_s. For a ^{52}Cr BEC, we obtain quantitative agreement with observations in recent experiments [1], and predict a collapse due to dipolar interaction to occur at positive a_s ($\sim 14 \pm 1 a_o$, using parameters similar to those in [1]). We have also performed calculations for BECs of alkali atoms, where the dipolar interactions are much weaker than in ^{52}Cr. We will show how our calculations may help measure small a_s and locate the zero- crossings. [1] T. Lahaye *et al.*, Nature **448**, 672 (2007); J. Stuhler *et al.*, Phys. Rev. Lett. **95**, 150406 (2005)

Holographic Storage of Multiple Coherence Gratings in a Bose-Einstein Condensate

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Recently, the conversion of quantum state between atoms and photons has been an important subject in the field of quantum information processing. However, the number of modes for the atom-photon conversion per atomic cloud was limited to one in the previous works. Here, in this poster, we report a novel technique capable of multiplexed storage of atomic coherence and independent conversion to photons in a single atomic cloud. We also performed the proof-of-principle experiment using superradiant Raman scattering in an elongated cloud of Bose-Einstein condensate[1].

Figure 1(a) and (b) show an experimental setup and an energy-level diagram, respectively. A rubidium condensate in the state $|1\rangle$ is first irradiated by an off-resonant "write" beam, and a small fraction of atoms is coherently transferred to the state $|2\rangle$ by emitting σ^+-polarized anti-Stokes photons along the long axis of the condensate. Then, an atomic coherence grating with a corresponding recoil wave vector is created in the atomic cloud. To convert the grating to photons, another "read" beam is applied to the atoms. When the read beam is counter-propagating to the write beam (to satisfy the Bragg condition), it diffracts off the grating in a superradiant way and σ^--polarized Stokes photons are emitted along the opposite direction to the anti-Stokes photons [Fig. 1(c)]. By contrast, when the read beam is not counter-propagating, Stokes process is strongly suppressed owing to the phase mismatching, and the grating is kept stored in the cloud [Fig. 1(d)]. Using this Bragg selectivity, multiplexing of the write-read process can be realized by applying two phase-matched write-read beam pairs [Fig. 1(e)].

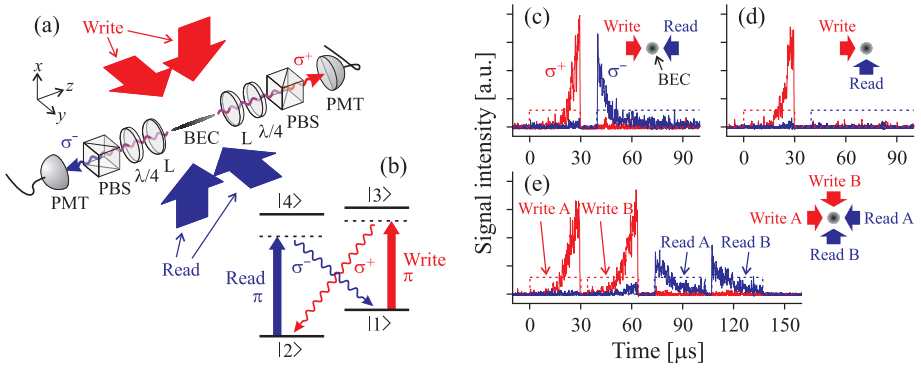

Figure 1: *(a) Experimental setup and (b) energy-level diagram. (c)-(e) show the observed waveforms of the scattered photons for various write-read configurations.*

[1]Y. Yoshikawa *et.al.* Phys. Rev. Lett. **99**, 220407 (2007).

Gross-Pitaevskii equation for a BEC of polarized molecules: anisotropic mass

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So far the theory of Bose-Einstein condensates (BEC) of polarized molecules was based on an ad hoc generalization of equations for spherical atoms. Here I adopt a rigorous approach to tunable low-energy dipolar interactions[1] and derive a non-linear mean-field Schrödinger equation for a harmonically-trapped condensate of polarized dipoles. I arrive at the following dipolar GPE for a condensate wavefunction Ψ

$$\left(-\frac{\hbar^2}{2M}\mathbf{\Delta}+U\left(\mathbf{r}\right)+g_0\left|\Psi\left(\mathbf{r}\right)\right|^2\right)\Psi\left(\mathbf{r}\right)+g_d\left(\frac{\partial^2}{\partial z^2}\left|\Psi\left(\mathbf{r}\right)\right|^2\right)\Psi\left(\mathbf{r}\right)=\mu_0\Psi\left(\mathbf{r}\right).$$

The derivative is taken along the polarizing field. The newly introduced coupling constant g_d is proportional to the off-diagonal scattering length characterizing mixing of s and d partial waves by the non-spherical dipolar collision process.

The corresponding result for the energy functional suggests introducing effective mass along the polarizing field,

$$M_{zz}^{\mathrm{eff}}\left(\mathbf{r}\right)=M/(1-8g_dM\,n\left(\mathbf{r}\right)/\hbar^2),$$

where the number density $n(r)=|\Psi(r)|^2$. The mass remains "bare" (M) for the motion perpendicular to the polarizing field. Effectively, the dipolar interactions alter molecular mass. The resulting effective mass is anisotropic: to the leading order the mass is altered only for the motion along the polarizing field. For a typical BEC of alkali-metal atoms the effective mass is reduced by 10% from it's bare value. For molecules, the mass may be reduced by a factor of 1,000.

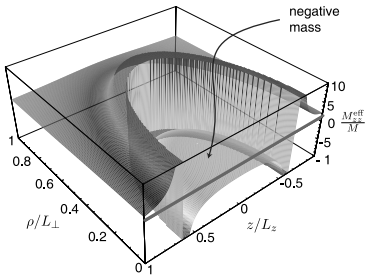

Figure 1: *Effective anisotropic mass $M_{zz}^{\mathrm{eff}}(\mathbf{r})$ as a function of position for a condensate cloud in a harmonic trapping potential. The BEC is mechanically unstable in the region of negative effective mass.*

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Feshbach Resonances in ultracold ^{40}K + ^{87}Rb mixture

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We report a theoretical study of Feshbach resonances in a ^{40}K + ^{87}Rb mixture at ultracold temperatures using accurate interaction potentials[1] in a full quantum-mechanical coupled channel calculation. Feshbach resonances in the initial collision open channel ^{40}K($f = 9/2$, $m_f = -9/2$) + ^{87}Rb ($f = 1$, $m_f = 1$) are found to agree with previous measurements, leading to precise values of the singlet and triplet scattering lengths for the system. We predict additional Feshbach resonances within experimentally attainable magnetic fields for other collision channels, and propose a realistic scheme for formation of stable ultracold KRb molecules using Feshbach-optimized photoassociation (FOPA)[2].

[1] A. Pashov et al., Phys. Rev. A **76, 022511 (2007)**
[2] P.Pellegrini et. al., Arxiv. Article ID 0806.1295

Singly excited doublet $^7Li_2 + {}^7Li$ potential energy surface for the formation of ultracold trimers

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With the success of ultracold molecular formation among the alkali metals over the last few years, the dynamics of molecules in an ultracold trap has become an important topic of interest to many physicists. Both heteronuclear and homonuclear Lithium diatoms have been formed in the ground electronic state with great success using combinations of photoassociation and Feshbach resonances. Furthermore, recent theoretical proposals[1] have shown an efficient production of diatoms in the deepest vibrational states, thus allowing true ground state collisions. Recent theoretical studies of the spin aligned quartet ground state collisional process in both high vibrational states[2] and deeply bound vibrational states[3] have been done. To study the formation of ultracold trimers using photoassociation, accurate long and short range potential energy surfaces must be known. However, to date the study of the excited Lithium trimer has been restricted to only short ranges[4].

We present initial potential energy surface calculations of the excited Lithium trimer in the doublet state, $Li_2[X^1\Sigma_g^+] + Li[^2P_u]$, at both long and short ranges. The first ab initio surface to be calculated is the $^2A''$ surface with C_s symmetry, which can be extended to C_{2v} and $C_{\infty v}$ geometries for spectroscopic considerations. After which the $^2A'(2)$ states will be calculated giving the complete singly excited potential energy surface. The transition moments between the excited and ground doublet state are also calculated for each state. This surface and the corresponding transition moments will be used to calculate the scattering properties of the excited doublet state for both elastic and inelastic collisions. In addition to the scattering properties, the Feshbach resonances will also be calculated for the study of photoassociation production of ultracold $^7Li_3$.

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[2] G.Quéméner, Jean-Michel Launay and Pascal Honvault, Phys. Rev. A, **75**, 050701 (2007)
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[4] H.-G. Krämer, et al, Chem. Phys. Lett. **299**, 212 (1999)

Two-photon femtosecond photoassociation – better perspectives for coherent control?

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Photoassociation (PA) has emerged as a technique to create ultracold molecules in their electronic ground state. Since it requires in principle only the presence of optical transitions, PA presents itself as an ideal candidate for coherent control with short shaped laser pulses. First attempts at femtosecond PA were, however, hampered by what seemed to be technical difficulties[1]. Indeed, the broad bandwidth of femtosecond lasers appears to be an obstacle for PA rather than a tool for control: Only a small band of transition frequencies close to the atomic resonance contribute significantly to the PA yield, while at the same time, excitation of the atomic resonance needs to be avoided. Theoretically, picosecond pulses in a pump-dump scheme were suggested[2], since their bandwidth is better adapted to PA. However, picosecond pulse shaping has yet to be developed.
A non-resonant two-photon process might resolve the ostensible conflict of driving a narrow-bandwidth transition by a broad-bandwidth laser[3]. For excitation with more than one photon, constructive and destructive interferences can be achieved for different pathways of the field, in addition to the different pathways which the molecule can take. While two-photon absorption may pave the way toward coherent control of PA, the success of the scheme will ultimately depend on the involved electronic states and transition frequencies. Here we discuss the perspectives of two-photon femtosecond PA for alkali and alkaline earth metal dimers.

[1] W. Salzmann et al., Phys. Rev. A **73**, 023414 (2006). B.L. Brown, A.J. Dicks, and I.A. Walmsley, Phys. Rev. Lett. **96**, 173002 (2006).
[2] C.P. Koch, E. Luc-Koenig, F. Masnou-Seeuws, Phys. Rev. A **73**, 033408 (2006).
[3] D. Meshulach and Y. Silberberg, Nature **396**, 239 (1998).

Spectroscopy of Ultracold ^{41}K^{87}Rb Molecules using Resonance Enhanced 2-photon Ionization

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Ultracold polar molecules have attracted enormous interest for various applications such as quantum computation, ultracold chemistry, and elementary particle physics. One of the promising ways to create such ultracold molecules is to start with laser cooled atoms, associate them with Feshbach resonance and transfer them to the absolute ground state with Stimulated Raman Adiabatic Passage (STIRAP). To efficiently convert Feshbach molecules into abolute ground state moleules, finding a proper intermediate state is essential. Thus we set up an experiment to study Frank Condon factors between ground and excited states using ultracold molecules.

We start with a double species MOT of ^{41}K and ^{87}Rb, and photoassociate K and Rb by shining a laser beam red detuned from Rb D_1 line. In order to increase the photoassociation rate, we developed CMOT (Compressed-MOT) process, which simultaneously cools and compresses both clouds. Measured densities and temperatures were 2×10^{11} cm^{-3}and 400 μK for K and 4×10^{11} cm^{-3}and 100 μK for Rb, respectively. The photoassociated molecules radiatively decay to both singlet $X^1\Sigma^+$ and triplet $a^3\Sigma^+$ ground states. These molecules are ionized through resonance enhanced 2-photon ionization. Here 10ns-pulses from a dye laser with 10 Hz repetition rate were used. The ionized molecules are detected with a Channeltron. The spectrum of the vibrational energy levels were obtained with scanning the excitation frequency. The experimentally obtained energy levels match with those from *ab initio* calculations.

The increase in phase space density which is attained with the CMOT stage is also quite useful for an experiment aimed for quantum degeneracy. For example, recently we have successfully produced a BEC of 2×10^5 ^{41}K via evaporative cooling. It is known that ^{41}K and ^{87}Rb has several Feshbach resonances at low field. Thus once a proper transition for STIRAP is identified, the quantum degenerate mixture of ^{41}K and ^{87}Rb should serve as a good starting point from producing ultracold polar molucules.

Time-Domain Measurement of Spontaneous Vibrational Decay of Magnetically Trapped NH

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[2]*Harvard-MIT Center for Ultracold Atoms, Cambridge, MA 02138, USA*
[3]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
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The $v = 1 \rightarrow 0$ radiative lifetime of NH($X^3\Sigma^-, v = 1, N = 0$) is determined to be $\tau_{\mathrm{rad,exp.}} = 37.0 \pm 0.5_{\mathrm{stat}}\,^{+2.0}_{-0.8\,\mathrm{syst}}$ ms ms, corresponding to a transition dipole moment of $|\mu_{10}| = 0.0540^{+0.0009}_{-0.0018}$ D. To achieve sufficiently long observation times, NH($X^3\Sigma^-, v = 1$) radicals are magnetically trapped using helium buffer-gas loading. The rate constant for background helium-induced collisional quenching was determined to be $k_{v=1} < 3.9 \times 10^{-15}$ cm^{3}s^{-1}, which yields the quoted systematic uncertainty on $\tau_{\mathrm{rad,exp.}}$. With a new $ab\ initio$ dipole moment function and a Rydberg-Klein-Rees potential, we calculate a lifetime of 36.99 ms, in agreement with our experimental value.

A High Flux Continuous Source of Guided Polar Molecules

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A high flux cold guided source for translationally and rotationally cold molecules and atoms has been demonstrated. Building on our earlier work to create cold beams, we have been able to guide polar molecules (ND_3), separating them from a buffer gas of cold helium or cold neon. Continuous guided fluxes of 10^{11} molecules/second and unguided fluxes of more than 10^{14} molecules/second, with forward velocities in the range of 50-150 m/sec, have been achieved. Possible applications for this general, high flux beam source will be presented, including collisional studies, loading magnetic and electrostatic traps, and applications to precision measurement.

Microwave Trapping of Buffer Gas Cooled Molecules

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We describe progress towards the realization of a proposal[1] to capture cold Strontium Oxide (SrO) molecules in a high power microwave trap. Our proposed protocol for producing ultracold molecules is outlined schematically in Fig.1. Laser ablation of solid precursor [A] yields a molecular vapor in a buffer gas cell. The molecules are cooled in their translational and internal degrees of freedom by thermalization with 4.2 K helium buffer gas [B]. Part of the thermalized sample is extracted from aperture [C] in the cell wall. An electrostatic quadrupole guide [D] transports the rotationally excited $|J = 1, 2; m = 0\rangle$ states of the Boltzmann distribution to a differentially pumped UHV trapping region. Upon reaching the trap volume, molecules are continuously transferred into the trapped rotational ground state $|J = 0; m = 0\rangle$ using a dissipative optical pumping process [E]. The trapped molecules [F] are then cooled sympathetically (by collisions with ultracold atoms in an overlapping MOT, not shown) or evaporatively.

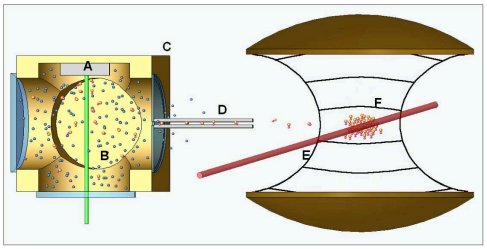

Figure 1: *Schematic of Cooling Procedure*

We present data that shows an ablation yield of $\sim 10^{12}$ molecules per pulse. Molecular fluorescence measurements of the beam flux indicate that an extraction efficiency of $\sim 10^{-3}$ can be attained in the effusive flow regime with an appropriate aperture. Data demonstrating transverse beam confinement by the electrostatic quadrupole guide are also shown. We obtain a flux enhancement factor of about 2.5 (averaged over all guided rotational states) for a guide of 10 cm length, consistent with numerical simulations. In addition, we present the results of a numerical calculation to determine the efficiency of the continuous dissipative loading scheme. For our guide geometry and a molecular beam with 4.2 K forward kinetic energy, a trap-loading efficiency of about 5×10^{-3} should be attainable. Finally, we describe measurements on microwave trap prototypes and outline the final cavity design. We have demonstrated resonator quality factors $Q \sim 5 \times 10^{-4}$, and have determined that 1.2 kW of input power can be dissipated while holding the mirror temperatures below 70 °C. Given these parameters, it should be possible to attain trap depths of $\sim$1.1 K for SrO. This work is supported by the ARO and the NSF.

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Towards Ultracold Mixtures and Molecules of Lithium and Ytterbium Atoms

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Exquisite control of interactions between ultracold atoms is now possible using scattering resonances. Ultracold diatomic molecules can also be formed using Feshbach and photoassociation resonances. Applying these methods between two different atomic species can lead to novel quantum phases of matter. These include Fermi superfluids with mass imbalance and strongly dipolar molecular superfluids. Further, stable ultracold dipolar molecular samples are promising systems for precise tests of fundamental symmetries and time variations of fundamental constants. We will report on progress towards building a system of ultracold lithium and ytterbium atoms to achieve these goals.

Ultracold Production and trapping of ultracold RbCs molecules

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The electric dipole-dipole interaction provides a strong, long-range, tunable anisotropic interaction between polar molecules. This is fundamentally different from most interactions studied between ultracold atoms, which are typically isotropic and comparatively short-ranged. Features of the dipole-dipole interaction can lead to many novel and exciting phenomena, such as long-range topological order[1], quantum chemistry[2], and the possibility for quantum computation[3]. Furthermore, the presence of closely spaced internal levels of the molecules, *e.g.* Ω-doublet, rotational, and vibrational levels, presents a host of new possibilities for precision measurement of fundamental physics[4]. A trapped *ultracold* sample of polar molecules, which will provide high densities and long observation times, is thus a necessary step for observing these phenomena.

We have recently confined ultracold RbCs molecules in an optical lattice trap[5]. Currently, these molecules are in high-lying vibrational levels of the $a^3\Sigma^+$ electronic ground state. Inelastic collision rates of these molecules with both Rb and Cs atoms have been determined for individual vibrational levels, across an order of magnitude of binding energies. A simple model for the collision process is shown to accurately reproduce the observed scattering rates.

We are currently implementing an improved version of a population transfer process, previously demonstrated in our lab with pulsed lasers[6], to transfer trapped molecules from the $a^3\Sigma^+$ state into the $X^1\Sigma^+(v = 0)$ absolute ground state. This state possesses a large electric dipole moment ($\mu \approx 1.3$ Debye). By this method, we expect to trap a sample of $> 10^4$ absolute ground state polar molecules ($X^1\Sigma^+$(v = 0; J = 0)) at a temperature of $\sim$20 μK and density of $\geq 10^9$ cm^{-3}. These molecular temperatures and densities should allow the observation of many of the aforementioned phenomena. We will report on our recent measurements of ultracold inelastic molecular collisions as well as our progress towards the trapping of absolute ground state polar molecules.

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[2]E.R. Hudson et al., Phys. Rev. A 73, 063404 (2006).
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[6]J.M. Sage et al., Phys. Rev. Lett. 94, 203001 (2005).

Repulsive shield between polar molecules

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We propose and analyze a technique that allows to suppress inelastic collisions and simultaneously enhance elastic interactions between cold polar molecules. The main idea is to cancel the leading dipole-dipole interaction with a suitable combination of static electric and microwave fields in such a way that the remaining van-der-Waals-type potential forms a three-dimensional repulsive shield. We analyze the elastic and inelastic scattering cross sections relevant for evaporative cooling of polar molecules and discuss the prospect for the creation of crystalline structures.

Magnetic trapping of atomic nitrogen (^{14}N) and cotrapping of NH ($X^3\Sigma^-$)

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We observe magnetic trapping of atomic nitrogen (^{14}N) and cotrapping of ground state imidogen (^{14}NH, $X^3\Sigma^-$). Both are loaded directly from a room temperature beam via buffer gas cooling. We trap approximately 1×10^{11} ^{14}N atoms at a peak density of 5×10^{11} cm^{-3} at 550 mK. The 12 +5/−3 s $1/e$ lifetime of atomic nitrogen in the trap is consistent with loss via elastic collisions with the helium buffer gas. This results in a limit on the ^{14}N-^{3}He inelastic collision rate coefficient of $k_{\rm in} < 2.2 \times 10^{-16}$ cm^3 s^{-1}. Cotrapping of ^{14}N and ^{14}NH is accomplished, with 10^8 NH trapped molecules at a peak density of 10^8 cm^{-3}.

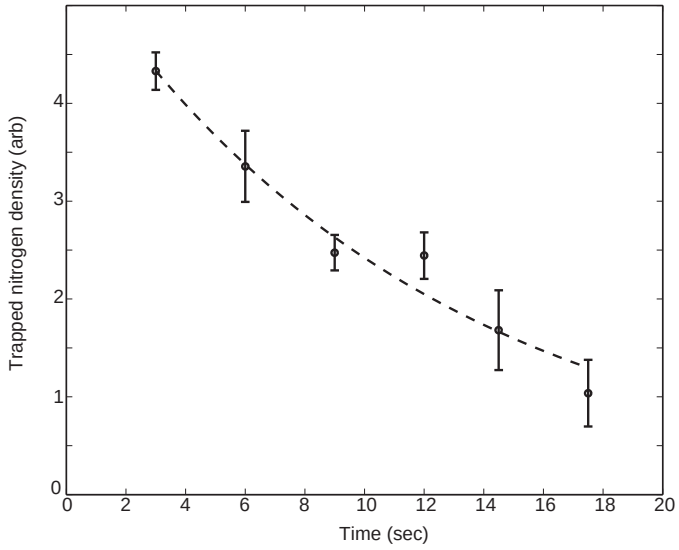

Figure 1: *Trapped nitrogen density vs. time after trap loading. An exponential fit (dashed line) to the data yields a* $1/e$ *trap lifetime of 12+5/−3 s.*

Photoassociation of ultracold LiCs molecules

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Ultracold molecular gases find many applications, reaching from high resolution spectroscopy over tests of the standard model to quantum chemistry and quantum computing [1]. Heteronuclear alkali dimers have a permanent dipole moment and therefore exhibit strong anisotropic and long-range electric dipole interactions. This allows precise control of internal and motional degrees of freedom by electric fields, thereby offering intriguing perspectives for the study of strongly-correlated many-body quantum systems. The LiCs molecule is an especially promising candidate for observing these interactions, since it posses the strongest dipole moment of all alkali dimers of up to 5.5 Debye in the ground state [2].

Here we present the photoassociation of ultracold LiCs molecules, stabilized by radiative decay. The molecules are detected using multiphoton ionization spectroscopy with a high-resolution time-of-flight mass spectrometer [3]. Active photoassociation in an overlapped Cesium dark SPOT/Lithium MOT, loaded from a single Zeeman-slower, is found to yield a strongly increased production rate compared to photoassociation by the trapping light of a two species MOT [4]. We identify photoassociation resonances in the $B^1\Pi$ potential up to $300\,\mathrm{cm}^{-1}$ below the $2S_{1/2}$-$6P_{3/2}$ asymptote. This spectroscopic data makes the yet unknown connection from the recently measured inner part of the $B^1\Pi$ state [5] to the molecular asymptote and yields a significantly improved value for the ground state dissociation energy. The perspectives for the production of LiCs molecules in the absolute ground state are evaluated and future experiments with an ultracold gas of polar LiCs molecules are outlined.

In addition we have studied scenarios for the alignment of ultracold dipolar molecules, based on combinations of static electric fields and strong laser fields [6]. For this purpose we calculated the static polarizability tensor for the ground state of all heteronuclear alkalis [7].

[1] See e.g. H. L. Bethlem and G. Meijer, Int. Rev. Phys.Chem. 22, 73 (2003)
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[4] SD Kraft *et al.*, J. Phys. B **39**, S993 (2006)
[5] A. Stein *et al.*, to appear in Eur.Phys. J. D, (2008)
[6] B. Friedrich et D. Herschbach, J. Phys. Chem. A 103, 10280 (1999)
[7] J. Deiglmayr *et al.*, submitted to J. Chem. Phys.

Quantum Gas of Deeply Bound Ground State Molecules

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Ultracold samples of molecules are ideally suited for fundamental studies in physics and chemistry. For many of the proposed experiments full control over the molecular wave function in specific deeply bound rovibrational states is needed. We create an ultracold dense quantum gas of deeply bound Cs_2 molecules in the $v = 73$ vibrational level of the $X^1\Sigma_g^+$ ground state, bound by more than 1000 wavenumbers or $h \times 30$ THz [1]. Weakly bound molecules are first produced on a Feshbach resonance from a Bose-Einstein condensate of cesium atoms. The molecules are then transferred to the $v = 73$, $J = 2$ level of the X state by coherent optical two-photon transfer using the STIRAP technique. The transfer efficiency exceeds 80%. Coherence of the transfer is demonstrated in a Ramsey-type experiment. We show that the sample is not heated during the transfer, essentially inheriting the high phase space density of the original atomic sample.
We discuss the progress for the implementation of the next step in which we aim to transfer the molecules into the rovibrational ground state $v = 0$, $J = 0$ of the X state. Our results show that the preparation of a quantum gas of molecules in arbitrary rovibrational levels is possible and that the creation of a Bose-Einstein condensate of molecules in the rovibronic ground state is within reach.

[1]Danzl *et al.*, manuscript submitted for publication

Trapping Stark decelerated cold molecules

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With a Stark decelerator, bunches of state-selected molecules with a controlled velocity and with longitudinal temperatures as low as a few mK can be produced. After molecules are decelerated to low enough velocity they can be loaded in a trap, and can be accurately studied exploiting the long interaction times afforded by a trap.

We will present the use of three different types of traps. One is an electrostatic trap that relies on the Stark shift of polar molecules. This trap has been used to trap OH, OD, CO$(a^3\Pi)$[1], and NH$(a^1\Delta)$[2] in this experiment. The lifetimes of several vibrationally or electronically excited states have been measured with unprecedented accuracy.

A second trap, existing of two magnetic coils, confines molecules using the Zeeman shift. So far it has been successfully used to trap metastable NH. In combination with an electric loading field, this trap can be used for a reloading scheme in which NH molecules are decelerated to a standstill in the metastable $(a^1\Delta)$ state, optically pumped via the $(A^3\Pi)$ excited state to the ground state, and finally magnetically trapped in this $X^3\Sigma^-$ state[3]. We will report the first results of the implementation of this scheme. A cheap and simple alternative to this technically challenging electromagnetic trap is to build a trap out of permanent magnets, as already demonstrated in the group of Jun Ye (JILA). Until now we have used permanent magnets to retro-reflect ground state OH molecules and focus them transversally as well as longitudinally[4].

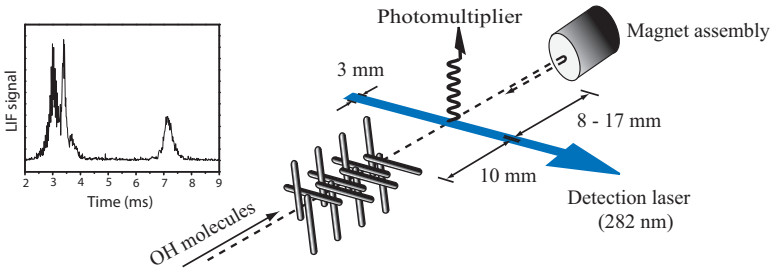

Figure : *The retro-reflection experiment of OH molecules. Only the last 7 (from a total 108) electrode pairs of the decelerator are shown. The graph in the upper left corner shows a time-of-flight profile for a beam of ground-state OH molecules decelerated from 390 m/s to 15 m/s. The undecelerated molecules arrive in the detection zone about 3 ms after their production in the source region, whereas the decelerated ones take some 4 ms longer.*

[1] The radiative lifetime of metastable CO $(a^3\Pi, v = 0)$, J.J. Gilijamse *et. al.*, JCP 127, 221102 (2007)

[2] Electrostatic trapping of metastable NH molecules, S. Hoekstra *et. al.*, PRA 76, 063408 (2007)

[3] Optical pumping of metastable NH radicals into the paramagnetic ground state, S.Y.T van de Meerakker *et. al.*, PRA 68, 032508 (2003)

[4] Reflection of OH molecules from magnetic mirrors, M. Metsälä *et. al.*, NJP, in press (may, 2008)

Progress Towards Forming Ultracold $^{85}Rb_2$ Molecules in an Optical Dipole Trap

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We report our progress towards the efficient production of ultracold Rb_2 molecules in a quasi electrostatic optical trap (QUEST) by photoassociation (PA). The QUEST is loaded from a magneto-optical trap (MOT), with additional cooling and compression stages to optimize the density and temperature. The trapped atom cloud is detected by absorption imaging. Molecules will be formed from the optically trapped atoms by PA to levels bound by $\approx$ 1-100 cm^{-1}, followed by radiative decay. Employing the QUEST will allow optical trapping of Rb_2 in the singlet $X\,^1\Sigma_g^+$ state, as well as enhancing greatly the PA rates for forming these ultracold molecules. We observed the enhancement of PA in the optical dipole trap compared to PA in the MOT alone. Trapped molecules in the dipole trap will be detected by resonant-enhanced multi-photon ionization (REMPI). We will present in more detail our progress in experimentally forming ultracold molecules in the dipole trap and progress toward experiments on collisions involving the trapped molecules. This work is supported by the National Science Foundation.

Weakly-bound molecules. Analysis by the Lu-Fano method coupled to the LeRoy-Bernstein model.

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We have performed experiments on the photo-associative spectroscopy of cold ^{87}Rb atoms, below the $5s_{1/2}$-$5p_{1/2}$ dissociation limit, producing weakly-bound excited molecules. With the trap loss spectroscopy technique we have recorded spectra, which exhibit the the 0_g^-, 0_u^+ and 1_g molecular vibrational series. The measured energies of the molecular levels allow us to determine properties of the molecular potentials.
Such weakly-bound molecules are described by the dipole-dipole atom interaction which varies, according to the molecular symmetry, either as $1/R^3$ or as $1/R^6$, where R is the inter-nuclear distance. The eigen energies of the weakly-bound molecules are then very close to those obtained by the well-known LeRoy-Bernstein model. The discrepancies to the LeRoy-Bernstein law are due to the short distance behavior of the molecular potential or to couplings to other molecular potentials due to interactions, for example spin-orbit or spin-spin interactions. The analysis of the discrepancies reveals these interactions.
To analyze the data, we have adapted the Lu-Fano method - extensively applied to Rydberg atoms in the past - to the weakly-bound molecules. Using the LeRoy-Bernstein law, a *molecular vibrational quantum defect* is defined and derived from the data. Its variation versus the binding energy gives the Lu-Fano graph which allows us to characterize the molecular potential and the interactions.
From the experimental data of te 0_g^- state, we obtain a Lu-Fano graph with a linear shape which is the signature of the short range behavior of the molecular potential [2]. A model for the barrier allows us to connect the slope to its location. The method has also been applied to 0_g^- levels of ^{85}Rb and ^{133}Cs [3].
The Lu-Fano graph of the 0_u^+ molecular levels exhibits sharp variations, signature of a coupling with a neighboring molecular series. The coupling is due to the spin-orbit and spin-spin interactions in the molecule [4]. A two series model allows us to evaluate the coupling, to identify two perturbing levels of the $5s_{1/2}$-$5p_{3/2}$ 0_u^+ series. A strong wave function mixing is deduced suggesting an efficient scheme for cold molecule formation. We also predict the energy position and the width of its first pre-dissociated level, which was confirmed by an experimental signal. The method has also been successfully applied to data of Cs_2 [5].

[1]laurence.pruvost@lac.u-psud.fr
[2]H. Jelassi, B. Viaris De Lesegno, L. Pruvost, Phys. Rev. A. 73, 32501, 2006
[3]H. Jelassi, B. Viaris De Lesegno, L. Pruvost, AIP Conference Proceedings ; ISC 2007 935 p. 203, 2007
[4]H. Jelassi, B. Viaris De Lesegno, L. Pruvost, Phys. Rev. A. 74, 12510, 2006
[5]H. Jelassi, B. Viaris De Lesegno, L. Pruvost, M. Pichler, W. Stwalley, submitted to Phys. Rev. A

Lifetime of exotic dimers of ultracold metastable helium

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We shall present results of two-photon photoassociation experiments dealing with a gas of helium atoms in the 2^3S_1 metastable state taken to a temperature range of 2 to 10 μK by evaporative cooling in a magnetic trap (see Figure 1). Atom-molecule dark resonance signals, as well as Raman signals provide information on the exotic molecules in the least bound state ($J = 2,\ v = 14$) of the interaction potential between two spin-polarized metastable atoms. The intrinsic lifetime of this dimer is derived from measuring the line width of the signals[1], after eliminating the contribution of the thermal broadening. We interprete the molecule lifetime in terms of ionization process. As the two metastable atoms are spin polarized when they collide and form the molecule, Penning ionization is inhibited by the electronic polarization, unless spin relaxation takes place, resulting from the weak spin dipole coupling between the quintet ${}^5\Sigma_g^+$ and the singlet ${}^1\Sigma_g^+$ states. We shall present a theoretical calculation of the molecular lifetime [2] and compare it with a previous estimate [3]. We shall discuss the discrepancy between these theoretical values and our experimental measurement. The possible influence of atom-molecule inelastic collisions will also be discussed.

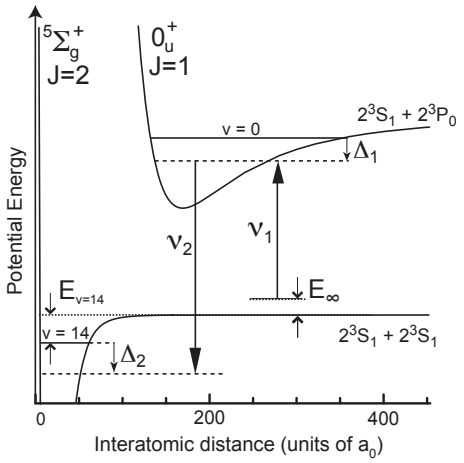

Figure 1: *Two-photon photoassociation of spin-polarized metastable helium.*

[1]S. Moal et. al, Phys. Rev. A, **75**, 033415 (2007)
[2]M. Portier, PhD thesis, available at http://tel.archives-ouvertes.fr/tel-00258383
[3]T. Beams et al., Phys. Rev. A, **74** 014702 (2006)

Formation of deeply bound molecules via chainwise adiabatic passage

Elena Kuznetsova[1,2], P. Pellegrini[1], R. Côté[1], M. D. Lukin[2,3], S. F. Yelin[1,2]

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Ultracold molecular gases open possibilities for studyng new exciting physical phenomena and their applications, such as testing fundamental symmetries, precision spectroscopy, ultracold chemistry, simulation of condensed matter systems and quantum computing. Dense samples of ultracold molecules in their ground rovibrational state $v = 0, J = 0$ are required for many of these applications. Currently translationally ultracold (100 nK - 1 mK) molecules are produced by magneto- and photoassociation techniques. These molecules, however, are vibrationally hot, being formed in high vibrational states near the dissociation limit of the electronic ground state. Therefore, once created, molecules have to be rapidly transfered to the ground rovibrational state.

We suggest and analyze a novel technique for efficient and robust creation of dense ultracold molecular ensembles in their ground rovibrational state. In our approach a molecule is brought to the ground state through a series of intermediate vibrational states via a multistate chainwise Stimulated Raman Adiabatic Passage (c-STIRAP) technique. We study the influence of the intermediate states decay on the transfer process and suggest an approach that minimizes the population of these states, resulting in a maximal transfer efficiency. We apply the technique to bosonic, fermionic and mixed alkali dimers, taking into account major decay mechanisms due to vibrationally inelastic atom-molecule and molecule-molecule collisions. As an example, we analyze the formation of $^{87}Rb_2$ starting from an initial Feshbach molecular state. Numerical analysis suggests a transfer efficiency $> 90\%$, even in the presence of strong collisional relaxation as are present in a high density atomic gas.

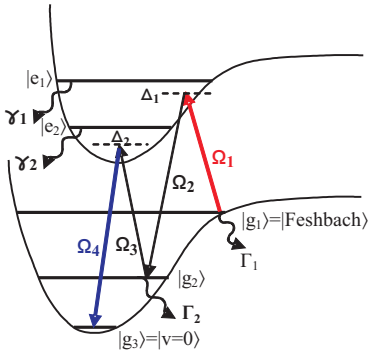

Figure 1: *Schematic showing the multistate chainwise STIRAP transfer from the Feshbach state* $|g_1\rangle$ *to the ground* $|g_3\rangle = |v = 0\rangle$ *state*

Cold Rydberg atom pair excitation in the presence of AC/DC electric fields

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We present experimental results that show a significant yield of nP atoms after excitation of nS Rb Rydberg atoms from a MOT using a pulsed dye laser, where $29 < n < 37$. The observed nP population is quadratically dependent on the nS atomic density. Such results are naturally attributed to binary collisions. However, this cannot be the case here, because the interaction between Rb nS atoms is repulsive. In this experiment, the AC Stark effect, dipole dipole interactions, and DC Stark effect work together to create a nonvanishing final population of $nP(n-1)P$ pairs. The background electric field and multipole interactions cause an admixture of $nS-nS$ character into the $nP(n-1)P$ pairs. The AC Stark shift from the laser pulse shifts the intermediate state into resonance with the $nP(n-1)P$ final pair. We compare our results to calculations done by numerically solving the density matrix equations for a two-photon excitation of the $nP(n-1)P$ pair state at $0.55 < R < 1.8$ μ. This leads to an estimated $32P$ to $32S$ signal ratio of 3.9 %, which is in excellent agreement with the experimental value of 2.6 %. The principal quantum number dependence of $nP/(nS)^2$ population was also measured, and it was shown to be consistent with our model. During the presentation, we will also discuss the DC electric field dependence. We believe that the control of electric field effects with regard to Rydberg atom interactions is important in order to use these novel and interesting systems for dipole blockade and quantum computation.

Rovibrational Dynamics and Photoassociation of Cold Heteronuclear Dimers in Electric Fields

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A comparative study of the effect of a static homogeneous electric field on the rovibrational spectra of several polar dimers in their $X^1\Sigma^+$ electronic ground state is performed. Focusing upon the rotational ground state within each vibrational band, results for energies and various expectation values are presented. For moderate field strengths the electric field-induced energy shifts, orientation, alignment, and angular motion hybridization are analyzed up to high vibrational excitations close to the dissociation threshold [1].

Furthermore, the formation of ultracold molecules via stimulated emission followed by a radiative deexcitation cascade in the presence of a static electric field is investigated. By analyzing the corresponding cross sections, the possibility to populate the lowest rotational excitations via photoassociation is demonstrated [2]. The modification of the radiative cascade due to the electric field leads to narrow rotational state distributions in the vibrational ground state [3].

[1] R. González-Férez, M. Mayle, P. Sánchez-Moreno and P. Schmelcher, to be published

[2] R. González-Férez, M. Weidemüller and P. Schmelcher, "Photoassociation of Cold Heteronuclear Dimers in Static Electric Fields", Phys. Rev. A **76**, 023402 (2007)

[3] R. González-Férez, M. Mayle and P. Schmelcher, "Formation of Ultracold Heteronuclear Dimers in Electric Fields", Europhys. Lett. **78**, 53001 (2007)

Stark deceleration of cold lithium hydride molecules

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We present recent results on the Stark deceleration[1] of cold lithium hydride molecules to low velocity. We produce pulsed beams of LiH, with a translational temperature of 1 K, by laser ablation of lithium into a supersonically expanding carrier gas containing hydrogen[2]. Most of the molecules are formed in the strong-field seeking rotational ground state which is unsuitable for slowing in the Stark decelerator. We therefore prepare the molecules in the weak-field seeking component of the first rotationally excited state by driving the rotational transition with narrowband radiation at 444 GHz. The molecules then enter a 100-stage Stark decelerator where switched electric field gradients are used to slow them down. Finally, the molecules are detected by laser induced fluorescence at 367 nm. In the electric field of the decelerator, the Stark shift of LiH is far from linear, unlike many of the molecules that have been decelerated previously. Using this apparatus, we have reduced the velocity of the molecules from an initial 420m/s down to a trappable 53m/s, corresponding to a 98.5% reduction in kinetic energy.

The work we present is one component of a project to produce ultracold molecules by sympathetic cooling with ultracold atoms. We plan to trap cold LiH together with ultracold Li. Elastic atom-molecule collisions will cool the molecules, while inelastic collisions will tend to lead to trap loss. It is likely that the ratio of elastic to inelastic processes will be highly unfavourable unless the inelastic processes are energetically forbidden[3,4]. Thus, both atoms and molecules should be trapped in their lowest-lying states. We consider some possible trapping geometries.

[1] H. L. Bethlem, G. Berden and G. Meijer, Phys. Rev. Lett. **83**, 1558 (1999)

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[3] M. Lara, J. L. Bohn, D. Potter, P. Soldán and J. M. Hutson, Phys. Rev. Lett., **97**, 183201 (2006)

[4] P. S. Zuchowski and J. M. Hutson, arXiv:0805.1705v1 (2008)

Dynamics of polar molecules in alternating gradient guides and decelerators

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Neutral particles can be guided using electric field gradients that focus in one transverse direction and defocus in the other, alternating between the two directions. Such a guide is suitable for focussing and decelerating polar molecules that are attracted to strong electric fields, which unlike their weak-field seeking counterparts cannot be confined using static fields[1]. Nonlinear forces are always present in these guides and can severely reduce the phase space acceptance. Using approximate analytical techniques, along with numerical methods, we calculate the influence of the most important nonlinear forces, and show how to choose the guide parameters so that the acceptance is maximized[2].
We have built a 1 m long alternating gradient guide with a four-rod geometry, and a 21-stage alternating gradient Stark decelerator with a two-rod geometry. These we have used to guide and decelerate YbF and CaF molecules. We present our experimental results on guiding and deceleration, and explain the results using some simple models as well as detailed numerical simulations.

[1] H.L. Bethlem, M.R. Tarbutt, J. Küpper, D. Carty, K. Wohlfart, E.A. Hinds and G. Meijer, J. Phys. B. **39**, R263 (2006)

[2] M. R. Tarbutt and E.A. Hinds, arXiv:0804.2077v1

A Near Quantum Degenerate Gas of Triplet $v = 0$ Polar Molecules

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We report on the creation of an ultracold dense gas of polar molecules from an ultracold mixture of Rb and K. Using a single step of STIRAP (STImulate Raman Adiabatic Passage), we demonstrated efficient state transfer from weakly-bound Feshbach molecules to the triplet rovibrational ground state. The triplet ground molecular gas has a density of $10^{12}\ cm^{-3}$ with quantum degeneracy $T/T_F = 3$. The ground-state molecules exhibit an permanent electric dipole moment. We will report our recent measurement of the permanent electric dipole moment. We will also present our progress toward state transfer to the singlet rovibrational ground state.

A Simple Model for Feshbach Molecule Bound States

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A Feshbach resonance and its associated bound state play an essential role in many experiments with ultracold atomic gases and lattices. We present simple models for such a bound state that applies beyond the limit of universality. The scale length $\bar{a}$ associated with the long-range van der Waals potential[1] provides key length and energy scales for classifying resonance properties[2]. A model of interacting closed and open channels, represented by square wells of width $\bar{a}$, gives a simple coupled equation similar to that of multichannel quantum defect theory for finding the energy of the near threshold bound state. The closed channel fraction Z in the eigenstate is readily found from the solution. The "box" model gives good agreement with full coupled channels calculations of the binding energy and Z for a wide range of resonances spanning many orders of magnitude in width and can be extended to overlapping resonances.

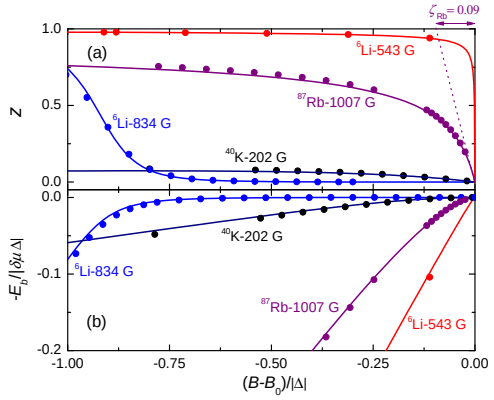

Figure 1: *Energy (b) and closed channel fraction Z (a) of selected Feshbach resonances, labeled by species and resonance position B_0. Lines are from a "box" model, and points are from full coupled channels calculations. Detuning of magnetic field B from B_0 is given in units of the resonance width Δ and binding energy E_b in units of $\delta\mu\Delta$, where $\delta\mu$ is the magnetic moment difference between the separated atoms and the "bare" closed channel molecular bound state.*

[1] G. F. Gribakin and V. V.Flambaum, Phys, Rev. A 48, 546 (1993)
[2] T. Köhler, K. Goral, and P. S. Jullienne, Rev. Mod. Phys. 78, 1311 (2006)

Giant formation rates of ultracold molecules via Feshbach Optimized Photoassociation

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Ultracold molecules have attracted a lot of attention due to their broad potential applications in metrology, high precision spectroscopy or quantum computing. The ability to form and control ultracold molecules has drastically improved over the last decade but producing stable molecules in their lowest vibrational levels still remains challenging. We present a theoretical investigation of the photoassociation of atoms in the vicinity of a Feshbach resonance for the production of ultracold stable molecules. Full molecular quantum coupled-channel calculations showed that large molecular formation rates can be obtained, with enhancement of several orders of magnitude over off-resonance cases. We illustrate this effect with both homonuclear and heteronuclear dimers. We will also present a simple analytical model for the photoassociation rates.

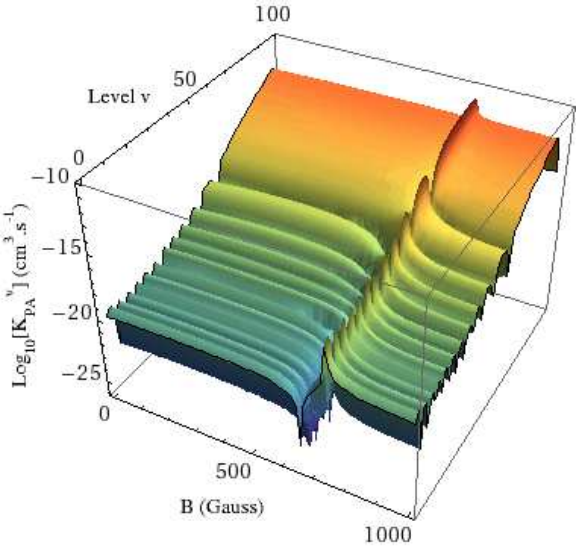

Figure 1: *Photoassociaitonn rates to the excited vibrational levels v of the* $1^3\Sigma_g^+(2s+2p)$ *of* $^7Li_2$ *as function of the magnetic field B showing the enhancement as we cross the Feshbach resonance at 735G.*

Observation of a Shape Resonance in Cold Ground State Rb_2 Molecule Formation

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About a decade ago, cold ground state Rb_2 molecules were detected for the first time in magneto-optical traps[1]. The formation of such molecules is due to photoassociation process by the trapping laser beam, which is by itself very surprising. In the last years, several experiments were devoted to trap such cold molecules, promoting a great deal of possibilities in the investigation of cold molecule collisions. However, the molecule formation due to photoassociation by the trapping laser still presents several open questions. In this work, we investigate the molecule formation rate as a function of the atomic sample temperature. Briefly, there are three phases in the experiment: i) trapping; ii) molasses; and iii) probe phase. First, using a standard MOT the ^{85}Rb atoms are trapped. Then for 4 ms, a molasses phase is applied, and the atoms are cooled. The final temperature of the atomic sample is determined by time of flight technique. In the probe phase, the atoms are illuminated by the trapping laser beam to form the cold molecule. And in the sequence, a pulsed dye laser (1 mJ/pulse, 4 ns, λ = 603 nm) photoionizes the cold molecules. The ions are collected by a channeltron and analyzed by a boxcar integrator gate. By time of flight the atomic ions can be discriminated from the molecular ions. The number of trapped atoms is determined by fluorescence. All these parameters allow us to measure the cold ground state Rb_2 molecule formation rate as a function of the atomic temperature (fig.1). We observed a peak around 130 μK, which is consistent with the existence of a partial wave resonance[2]. We have also measured the molecular temperature as a function of the atomic sample temperature. Our results indicate that more theoretical work is necessary in order to understand the photoassociation process due to the trapping laser beam. This work has received financial support from Fapesp and CNPq - Brazilian Agencies.

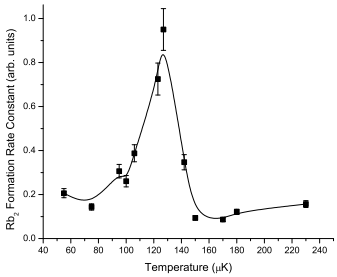

Figure 1: *Cold ground state Rb_2 molecule formation rate as a function of the atomic temperature.*

[1] A. Fioretti et al., Phys. Rev. Lett. 80, 4402 (1998); C. Gabanini et al, Phys. Rev. Lett. 84, 2814 (2000).
[2] H. Boesten et al., Phys. Rev. Lett. 77, 5194 (1996).

Low-Temperature Collisions Utilizing Trapped OH

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Advances in cold molecules promise to profoundly impact research on precision measurement, quantum information, and controlled chemistry. We employ a Stark decelerator to slow a supersonic beam of ground-state OH molecules from 500 m/s to 36 m/s. We subsequently trap a 70 mK sample of the decelerated molecules at a density of 10^6 cm^{-3} within a magnetoelectrostatic trap (MET) whose center lies 1 cm from the decelerator exit. We have improved upon our previous MET design[1] by replacing the high-current coils with permanent ring magnets and reducing the trap dimensions to better match the molecular packet. A large electric field is applied to the nickel coatings of the permanent magnets to stop the OH packet within the magnetic quadrupole. We report progress toward observation of collisions between trapped OH and a tunable atomic beam of He with an energy resolution of 9 cm^{-1}. The velocity of the colliding He beam is adjusted by varying the nozzle temperature of the pulsed valve, thereby tuning the OH-He center-of-mass collision energy from $\sim$ 60–250 cm^{-1}. Inelastic cross sections for transitions to excited spin-orbit and rotational levels can be probed over this energy range. In addition to being completely open in the radial dimension, our trap design allows for the application of a polarizing electric field to the trapped sample to facilitate future polar-molecule collision studies.

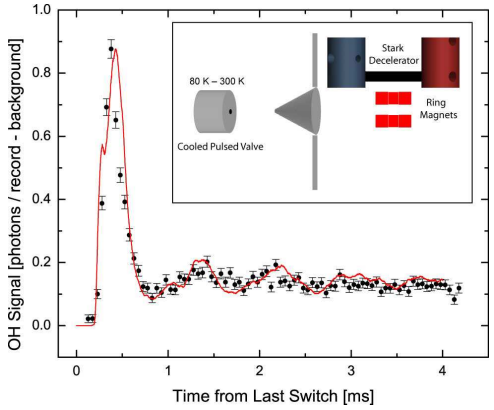

Figure 1: *Time-of-flight data displaying OH molecules as they are stopped and trapped within the MET. The solid line is the result of Monte Carlo simulation. The large initial peak at 400 μs is the stopped OH packet, while the trapped molecules undergo oscillations beyond $\sim$1 ms. The inset is an illustration of the MET and decelerator along with the pulsed valve and skimmer used for collision studies.*

[1] B. C. Sawyer *et al.*, Phys. Rev. Lett. **98**, 253002 (2007).

Nearly degenerate levels in Cs_2 with amplified sensitivity to variation of μ= m_e/m_p

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Astrophysical searches currently yield stringent bounds at the level $10^{-15}/year$ on the time variation of μ [1]. From the perspective of laboratory searches for time-variation of μ, the differing sensitivity of molecular vibrational levels to variations in μ offers an interesting possibility. For a diatomic molecule in a strongly-bound vibrational state ν, the sensitivity of the vibrational energy E_ν to a fractional change in μ is given by $\partial_\mu E_\nu = E_\nu/2$. Thus a high-lying vibrational state can have much greater sensitivity to changes in μ than a low-lying vibrational level. A transition between a pair of nearly-degenerate vibronic levels one from a deep electronic state, the other from a shallow electronic state– possesses both a high relative and a high absolute sensitivity to the time-variation of μ. The ground state manifold of Cs_2 consisting of the overlapping deep $X^1\Sigma_g^+$ and shallow $a^3\Sigma_u^+$ electronic potentials is an attractive candidate for implementing such a scheme.

We present spectroscopic evidence verifying the presence of a near degeneracy in the ground vibronic levels of Cs_2. Starting with spin-polarized ultracold ($T = 100\mu K$) Cs atoms ($F = 4, m_F = 4$), we use a two-color photoassociation process via the $(2)0_g^-$ excited state to observe the rich hyperfine and rotational sub-structure in deeply-bound vibrational levels of the $a^3\Sigma_u^+$ ground state of Cs_2. The observed line strengths and positions agree with predictions for the long-range part of the $a^3\Sigma_u^+$ state. We report the presence of an unexpected line in the $\nu_a = 37$ vibration level. We attribute this line to hyperfine and second-order spin-orbit mixing of nearly-degenerate singlet and triplet levels in the ground-state manifold. The fits to our data can accurately predict the position of other nearby, unobserved $X^1\Sigma_g^+$ state sublevels ideal for use in the proposed experiment.

Based our spectroscopic data, we calculate the amplified relative and absolute sensitivity of a transition between such pairs of nearly degenerate vibrational levels of the $X^1\Sigma_g^+$ and $a^3\Sigma_u^+$ electronic potentials. Recent advances in the production of ultracold Cs_2 molecules should make it possible to carry out narrow linewidth spectroscopy of such nearly degenerate levels [2]. We propose experiments that would make it possible to detect to changes in μ at the level 10^{-17}/year or better [3].

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[2]C. Chin et al., Phys. Rev. Lett. 90, 033201 (2003); M. Mark et al., Europhys. Lett. 69, 706 (2005).

[3]DeMille et al. Phys. Rev. Lett. 100, 043202 (2008).

Many-body effects in the production of Feshbach molecules

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We have derived and implemented a non-Markovian Boltzmann-like equation for the dynamics of an ultracold thermal Bose gas. Our approach includes time-varying two-body interactions and accounts for rethermalisation effects in the atomic gas. The Boltzmann equation is recovered in the limit of long times and stationary interactions. We calculate the dynamics of the one-body density matrix, which can then be used to calculate quantities such as the production efficiency of Feshbach molecules. For the case of low molecule production efficiency, with a correspondingly small depletion of the atomic gas, our approach recovers the limit in which the efficiency is given by a weighted average over the two-body transition probability density. By considering higher depletions we see the onset of many-body effects, which reduce the predicted efficiency from the small-depletion limit. The nonlinearity of our equations leads to a saturation of the predicted molecule production efficiency, and allows us to examine a range of dynamical effects in ultracold gases.

Magnetic Trapping and Zeeman Relaxation of NH Molecules

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NH molecular radicals are magnetically trapped in the presence of a helium buffer gas and their Zeeman relaxation and energy transport collisional cross-sections with helium are measured. Molecules are loaded from a molecular beam into a cold buffer gas cell in a 4T anti-Helmholtz magnetic trap. The NH-He energy transport cross-section is measured to be $2.7\pm\ 0.8\times10^{-14}\mathrm{cm}^2$ at 710 mK. The inelastic (Zeeman state changing) cross-section is also measured to be $3.8\ \pm\ 1.1\times10^{-19}\mathrm{cm}^2$ at 710 mK, indicating a γ (elastic to inelastic cross-section ratio) of 7×10^4, in agreement with the theory of Krems et al (PRA 68 051401(R) (2003)). Cross-section measurements are obtained for the interaction of the molecular isotopes ^{14}NH, ^{14}ND, ^{15}NH and ^{15}ND with the helium isotopes He-3 and He-4.

Ultracold Molecules for Precision Measurements

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Optical lattice clocks based on ultracold neutral two-electron atoms were recently successful in achieving systematic uncertainties[1] near 1×10^{-16} and absolute uncertainties[2] below 10^{-15}, and in placing new limits on the gravitational coupling of fundamental constants[3]. This has demonstrated the place of two-electron alkaline earth atoms in the world of precision measurements. We have investigated the possibility of producing ultracold homonuclear molecules based on two-electron atoms such as ^{88}Sr, and using them in precision measurements. Such a molecular system would benefit from the ultracold temperatures and optical-lattice tight trapping techniques, while offering opportunities for precision measurements complementary to those available with atomic systems or astronomical observations. Particularly, homonuclear molecules present a model-independent system for tests of time variations of the proton-electron mass ratio. Creation and manipulation of dimers based on ultracold bosonic two-electron atoms is attractive due to the inherent simplicity of their zero-spin ground state molecular potentials[4,5]. The lack of hyperfine or magnetic structure removes many sources of loss, and combined with the existence of laser-accessible metastable molecular potentials allows optical transitions with branching losses of only $\sim 50\%$, on par with many atomic transitions. Further, the systematic sensitivity to stray magnetic fields is greatly reduced. We have determined that the molecules can be transferred from the weakly bound vibrational states to the absolute ground vibrational state in only two optical Raman steps, with low losses. Moreover, we showed that it should be possible to apply the Stark-cancellation optical lattice scheme to vibrational molecular transitions, enhancing the possibilities for precise and accurate spectroscopic measurements.

[1]A. D. Ludlow, T. Zelevinsky, G. K. Campbell, S. Blatt, M. M. Boyd, M. H. G. de Miranda, M. J. Martin, J. W. Thomsen, S. M. Foreman, Jun Ye, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, Y. Le Coq, Z. W. Barber, N. Poli, N. D. Lemke, K. M. Beck and C. W. Oates, "Sr Lattice Clock at 1×10^{-16} Fractional Uncertainty by Remote Optical Evaluation with a Ca Clock", *Science* 319, 1805 (2008).

[2]G. K. Campbell *et al.*, to be published.

[3]S. Blatt, A. D. Ludlow, G. K. Campbell, J. W. Thomsen, T. Zelevinsky, M. M. Boyd, J. Ye, X. Baillard, M. Fouché, R. Le Targat, A. Brusch, P. Lemonde, M. Takamoto, F.-L. Hong, H. Katori and V. V. Flambaum, "New Limits on Coupling of Fundamental Constants to Gravity Using ^{87}Sr Optical Lattice Clocks", *Phys. Rev. Lett.* 100, 140801 (2008).

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Laser-Induced Fluorescence of Metastable He_2 Molecules in Superfluid Helium

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Ionizing radiation events in superfluid helium result in the copious production of meta-stable He_2 molecules which have a 13 s radiative lifetime in the liquid.[1] We present results on detecting and imaging the molecules by driving them through many fluorescence-emitting transitions during their lifetime.

Figure 1 shows the lowest-lying electronic states and two relevant vibrational levels of the triplet molecules, as well as one cycling transition used to detect them. A single laser pulse at 905 nm can excite a molecule in the $a^3\Sigma_u^+$ state to the $d^3\Sigma_u^+$ state, where it will most often decay to the $b^3\Pi_g$ state emitting a detectable red photon at 640 nm. The $b^3\Pi_g$ state is then rapidly quenched back to the $a^3\Sigma_u^+$ state, and the cycle can be repeated.

We have confirmed that complications due to decays to the long-lived, excited vibrational levels of the $a^3\Sigma_u^+$ state, which would drastically reduce the number of times a molecule can be cycled, can be mitigated with the use of repumping lasers. For instance, a molecule which decays to the $a^3\Sigma_u^+(v=1)$ state, can be driven to $c^3\Sigma_g^+(v=0)$ state with a laser at 1073 nm where it will most often decay back to the $a^3\Sigma_u^+(v=0)$ state. Similarly, a laser at 1099 nm can be used to regain molecules which decay to the $a^3\Sigma_u^+(v=2)$ state.

This technique gives rise to a new method for detecting ionization events in superfluid helium with applications in the detection of gamma rays, ultracold neutrons, and WIMP dark matter. It also promises to be a powerful tool for visualizing turbulence in superfluid helium.

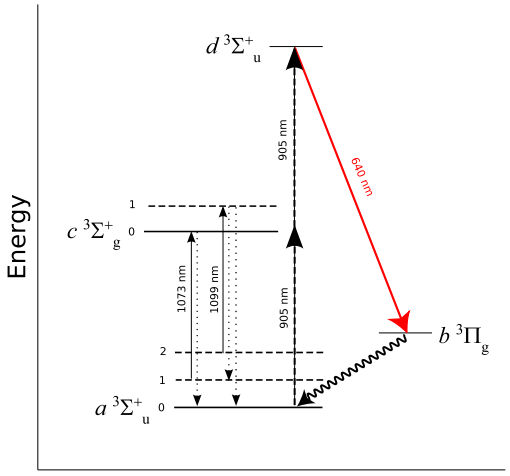

Figure 1: *Energy level diagram of the lowest lying triplet states of the He_2 molecule. The arrows indicate a cycling transition used to detect and image the molecules, as well as transitions used to repump molecules that decay to excited vibrational levels.*

[1] D. N. McKinsey *et al.*, Phys. Rev. A **59**, 200 (1999).

Barium Ion Trap Cavity QED

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We propose to use barium ions for studies of cavity quantum electrodynamics and quantum information. Barium has several properties which make it ideal for this purpose. Its states allow for the possibility of implementing either an optical qubit or hyperfine qubit. Additionally, unlike other ions, barium has its primary lines in the visible rather than in the UV. Cavity mirror technology is sufficiently advanced at these wavelengths to allow for the creation of high-finesse optical cavities. Cavities of this type are essential for creating the kind of fast, coherent interaction between internal ion states and cavity photons which will be pursued. The successful integration of ion trap and cavity QED technologies has exciting possibilities for the advancement of quantum information and quantum computation science. The experiment under construction will accomplish this integration by combining a miniaturized linear ion trap with a high-finesse optical cavity.

The effect of ion beam distribution temperature on lateral spread of implanted ions on a solid target

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Over the years the dimensions of electronics components have been reduced systematically by a factor of two every six years, as formulated in Moors law. However, continued miniaturizations, such as development of nano devices, have been hampered by several outstanding experimental difficulties associated with, in particular lateral spread of implanted materials. This is due principally to the statistical nature of ion-target collisions as well as natural distribution of ion implanted beam. For XLSI circuits lateral straggling is becoming more and more important. In this paper, we present the relationship between the initial temperature of extracted ions from a RF trap and the lateral spread of implanted ions on the solid surface. Ions extracted at different temperature from the trap are modeled based on action diagram method. These ions, after passing through an accelerator system, then interact with a thin layer of silicon. The results show the profound effect of ion temperature on the lateral spread of implanted ions on the surface. Also it shows the lateral spread could be controlled via temperature control of ion implanted distribution.

Temperature control of ion beam surface interaction using rf ion trap

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As we have showed in our first paper, controlling over temperatures of ion implanting beams has a profound effect on ion implanted distributed materials in ion-surface interaction and thereby changing the futures of nano electronics. In this paper we present a novel system in ion implantation for design and fabrications of nano materials. In this system ion beams from an ion implantation set-up will be trapped in an ion RF trap, cooled with buffer gas and then reaccelerated to desire energies. In such systems, because of the control over temperature of ions, NanoIonBeams with very narrow distributions can be obtained. Such systems will be modelled in this paper. Ion beams, with energy and emittances comparable from an Ion implantation system decelerated and trapped in an Ion RF trap and cooled with buffer gas, are simulated at different temperatures. The results of the simulation will be compared with experimental data. A good agreement between the experimental data and simulations will suggest the future set-up for ion-surface interaction systems.

Segmented Ion Traps for Quantum Computing

D. T. C. Allcock, M. J. Curtis, G. Imreh, A. H Myerson, D. J. Szwer, S. C. Webster, J. A. Sherman, D. N. Stacey, D. M. Lucas, A. M. Steane

Centre for Quantum Computation, Clarendon Laboratory, Oxford University, UK

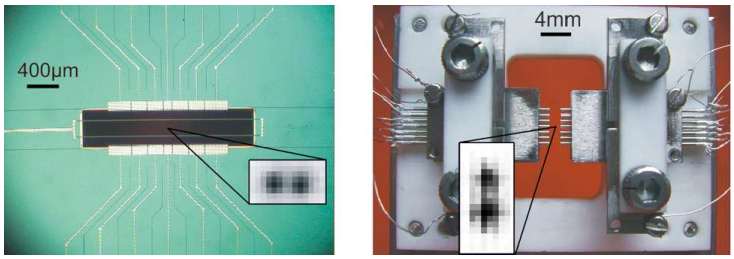

Figure 1: *The two traps with two Ca^+ ions loaded in each (insets).*

We report the successful loading of $^{40}Ca^+$ ions in two segmented radio frequency traps. Ion traps have been used to demonstrate coherent manipulation of the quantum states of a small number of ion qubits. Segmented electrodes incorporated into the structure of these traps are designed to allow for the creation of multiple trapping regions and ion transport along the axis of the trap. The development of these techniques should open the possibility of greatly expanding the number of ion qubits under simultaneous coherent control.

The first trap is a micro-scale, planar, chip-top trap fabricated by Sandia National Laboratories. Scaling down the trap size presents new challenges including increased heating rates and reduced trap depth. Trap loading is via two step photo-ionization in the trapping region in the presence of a calcium atomic beam from an oven source. We have achieved ion lifetimes of $\sim$90 minutes in this trap and observed heating rates of $\sim$70 Ks^{-1}.

The second trap is also segmented but built on a sub-millimetre scale by the University of Liverpool. This is intended to be an intermediate step in adapting techniques of ion transport to micro-scale traps without the attendant high heating rates and low trap depths. We will report on trapping and initial experiments in this trap.

Finally we present details of a further three traps under preparation at Oxford, two of which are of a planar design.

Scalable, efficient ion-photon coupling with phase Fresnel lenses for large-scale quantum computing

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Efficient ion-photon coupling is an important component for large-scale ion-trap quantum computing. We propose that arrays of phase Fresnel lenses (PFLs) are a favorable optical coupling technology to match with multi-zone ion traps. Both are scalable technologies based on conventional microfabrication techniques. The large numerical apertures (NAs) possible with PFLs can reduce the readout time for ion qubits. PFLs also provide good coherent ion-photon coupling by matching a large fraction of an ion's emission pattern to a single optical propagation mode (TEM_{00}). To this end we have optically characterized a large-numerical-aperture phase Fresnel lens (NA=0.64) designed for use at 369.5 nm, the principal fluorescence detection transition for Yb^+ ions. A diffraction-limited spot $w_0 = 350 \pm 15$ nm ($1/e^2$ waist) with mode quality $M^2 = 1.08 \pm 0.05$ was measured with this PFL. From this we estimate the minimum expected free space coherent ion-photon coupling to be 0.64%, which is twice the best previous experimental measurement using a conventional multi-element lens.

Fluorescence Imaging of Ultracold Neutral Plasmas

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Spatially-resolved fluorescence imaging of Ultracold Neutral Plasmas (UNP) produces a spectrum that is Doppler-broadened due to the thermal ion velocity and shifted due to the ion expansion velocity. Furthermore, sheet excitation of the plasma allows for localized analysis of the system without density variation. Using this technique, adiabatic cooling, electron-ion collisions, kinetic energy oscillations and velocity-changing collisions are studied for Ultracold Neutral Plasmas.

Trapped Rydberg Ions: From Spin Chains to Fast Quantum Gates

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We study the dynamics of Rydberg ions trapped in a linear Paul trap, and discuss the properties of ionic Rydberg states in the presence of the static and time-dependent electric fields constituting the trap. The interactions in a system of many ions are investigated and coupled equations of the internal electronic states and the external oscillator modes of a linear ion chain are derived. We show that strong dipole-dipole interactions among the ions can be achieved by microwave dressing fields. Using low-angular momentum states with large quantum defect the internal dynamics can be mapped onto an effective spin model of a pair of dressed Rydberg states that describes the dynamics of Rydberg excitations in the ion crystal. We demonstrate that excitation transfer through the ion chain can be achieved on a nanosecond timescale and discuss the implementation of a fast two-qubit gate in the ion chain.

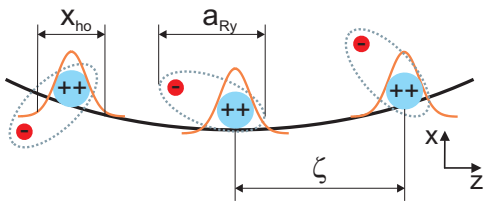

Figure 1: *Typical length scales in a chain of cold Rydberg ions in a linear Paul trap. The external trapping frequency is in the order of MHz with a corresponding oscillator length $x_{\rm ho}$ of approximately 10 nm. The interparticle spacing ζ, set by the equilibrium between the Coulomb forces among the ions and the external confinement, is typically about 5 μm. The third length scale is the size of the Rydberg orbit $a_{\rm Ry}$. Due to the scaling proportional to the square of the principal quantum number n it can assume values in the order of 100 nm and therefore become significantly larger than $x_{\rm ho}$. In this regime the Rydberg ion cannot be considered as a point particle but rather as a composite object, and its internal structure must be taken into account.*

[1] M. Mueller, L.-M. Liang, I. Lesanovsky, P. Zoller, *Trapped Rydberg Ions: From Spin Chains to Fast Quantum Gates*, arXiv:0709.2849

Progress towards distribution of entanglement in an ion trap array

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Trapped atomic ions have now demonstrated the basic requirements for quantum information processing on small numbers of qubits, and the major remaining challenges are to improve operation fidelity and scale up these techniques to larger numbers of ions. This will require the ability to entangle, distribute, and perform subsequent entangling operations on multiple atomic ions in a large number of trapping sites. One possible scalable architecture is to move the ions themselves around an array of microtraps [1] [2]. This requires complex multi-zone traps, a high level of control of the electric fields used to move the ions, and the ability to address the different zones in a phase coherent way. In practice, ambient fluctuations in the electric field at the ion and imperfect control of electrode potentials mean that the ion's motion is excited, which degrades the performance of two-qubit logic gates. In order to counteract these effects, coolant ions of a different species from the qubit can be simultaneously trapped, allowing re-initialization of the ground motional state of the ions prior to performing logic gates, without disturbing the quantum information.
We report on progress towards distribution of entangled atomic ions in a multi-zone trap array and the use of two species ion crystals ($^{24}Mg^{+}$ and $^{9}Be^{+}$) to prepare a well defined motional state after distribution.

[1] D. Kielpinski, C. Monroe and D. J. Wineland, Nature 417, 709 (2002)
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Individual addressing of trapped ions and coupling of motional and spin states using rf radiation

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We demonstrate for the first time two essential experimental steps towards realizing a novel concept for implementing quantum computing and quantum simulations with trapped ions[1]. The experiments were performed using the metastable $D_{3/2}$-state of laser cooled $^{172}Yb^{+}$-ions in a spatially varying magnetic field. When using π-transitions to repump ions from this metastable state back into the cycling cooling transition, the steady state cooling fluorescence rate is found to be proportional to the population in the "inner" $m = \pm 1/2$ states and stops because optical pumping populates the "outer" $m = \pm 3/2$ states. Population can be transfered coherently between inner and outer states by magnetic dipole transitions using rf radiation and single atoms can be addressed when the magnetic field and therefore the Zeeman splitting varies along the ion chain. Furthermore, the transition affects the ion's motional state: For the interaction in an inhomogeneous magnetic field, the Zeeman energy and thus the ion's equilibrium position may become state dependent and the coupling of internal and motional state is described by the *effective* Lamb-Dicke parameter η_{eff} and sidebands accompany the resonance[2].

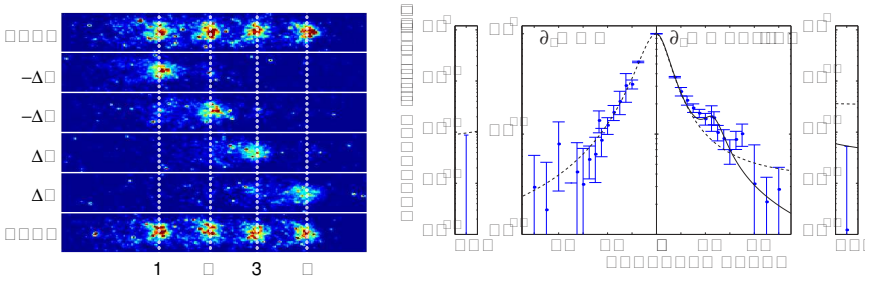

Figure 1: *a) Individually addressing single ions that are part of a linear Coulomb crystal composed of four ions. The uppermost and lowermost image are recorded without optical pumping (labeled 'NoOP') and all ions scatter light. For the intermediate pictures, the magnetic field direction is rotated allowing optical pumping, and the rf frequency was set to the expected resonance of one particular ion. Thus, all ions except one remain dark. b) Comparison of two symmetrized spectra recorded with a single ion in a constant magnetic field (left-hand side) and exposed to a magnetic field gradient (right-hand side). The dashed lines represent fits using a single Lorentzian (lhs and rhs), the solid line represents a fit using two Lorentzian lines (rhs). The motional sideband accompanying the spin resonance signifies coupling between the spin degree of freedom and the motion of the ion.*

[1]F. Mintert and C. Wunderlich, Phys. Rev. Lett. 87, 257904 (2001); C. Wunderlich, Laser Physics at the Limit (Springer, 2002), p. 261

[2]D. J. Wineland and W. M. Itano, Phys. Rev. A 20, 1521 (1979)

Observation of the Quadrupole Transition in a single cold $^{40}Ca^{+}$

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Trapped and cold $^{40}Ca^{+}$ ion is one of promising candidate of future optical frequency standards. We had measured the quadrupole transition of the $^{2}S_{1/2}$–$^{2}D_{5/2}$ of a single trapped and cold $^{40}Ca^{+}$ ion. Our experiments were performed with a single $^{40}Ca^{+}$ ion confined in a miniature Paul trap with a ring (r_0 = 0.8 mm), two endcaps ($2z_0$ = 2 mm) electrodes[1]. The pair of auxiliary rod electrodes was placed for compensating the stray electric field. For laser cooling, 397 nm and 866 nm lasers were carried out with commercial single-mode diode lasers (Toptica), which locking to Fabry-Perot interferometers and Optogalvanic (OG) signals respectively[2]. The laser at 729 nm for the clock transition $^{2}S_{1/2}$–$^{2}D_{5/2}$ was a Ti:sapphire laser (Coherent MBR-110), which locked to the high-finesse (F=3.5*10^{6}) ultra-low-expansion optical cavity. Single $^{40}Ca^{+}$ ion was loaded from neutral Ca atoms into the trap by electron ionization in the trap directly. The trapped single ion was laser cooled with the 397 nm and 866 nm lasers. The narrowing of fluorescence spectrum had been observed by minimizing the micromotion with optimizing the compensation voltages using the rf-photon correlation technique[3]. The quadrupole transition spectra were observed by the electron shelving method. Three magnetic field coils were used to generate an arbitrary magnetic field at the position of ion. The Zeeman components of $^{2}D_{5/2}$ were measured by pulse-light sequence.

We thank Dr. H. Shu, Prof. G. Huang, Ms. J. Li, Prof. L. Chen and Prof. F. Vedel for the discussion and help. This work was carried out with the support of the National Natural Science foundation of China under Grant No: 60490280; National fundamental research program Grant No: 2005CB724500

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Temperature Dependence of Electric Field Noise Above Gold Surfaces

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Dense arrays of trapped ions provide one way of scaling up ion trap quantum information processing. However, miniaturization of ion traps is currently limited by sharply increasing motional state decoherence at sub-100 μm ion-electrode distances. This decoherence has been demonstrated to be thermally driven, providing a plausible route to reduce it. In our experiment, we measure the heating rates out of the motional ground state of a single Sr^+ ion as a function of electrode temperature in $6-120$ K range. At 6 K, heating rates are observed to be as low as two quanta per second. The noise exhibits an approximate 1/f spectrum around 1 MHz, and grows rapidly with temperature as T^β for β from 2 to 4. The data fit a model with a continuous spectra of thermally activated random processes, and are consistent with microfabricated cantilever measurements of non-contact friction, but do not extrapolate to the DC measurements with neutral atoms or contact potential probes.

Frequency metrology on a single, trapped ion in the weak binding limit: The $3s_{1/2}$–$3p_{3/2}$ transition in Mg^+

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Radio frequency ion traps allow to prepare a sample of cold ions subject to low systematic uncertainties, which enabled the most precise spectroscopic measurements ever made[1]. So far, virtually all absolute frequency measurements on trapped ions have been performed on very narrow transitions in the so-called strong binding limit, where the secular frequency of the ion exceeds the natural linewidth. In this case the spectrum consists of a carrier and a number of sidebands that can be addressed individually. Spectroscopy on the carrier eliminates Doppler and recoil shifts, an important prerequisite for the tremendous accuracies achieved. However, a range of interesting transitions have large linewidths that make it hard if not impossible to reach the strong binding limit. Examples include astrophysically relevant transitions[2] and the study of exotic nuclei by measuring isotope shifts of strong dipole transitions[3]. In this regime, heating and cooling distorts the observed line strongly, thereby limiting the spectroscopic accuracy. We developed a new measurement technique based on continuous sympathetic cooling of an ion chain and spatially resolved detection which overcomes these limitations and allows to observe a symmetric, well understood lineshape. To demonstrate the method we measured the absolute frequency of the $3s_{1/2}$–$3p_{3/2}$ transition in a single trapped Mg^+ ion at 280 nm (linewidth 41.8 MHz). This line is a so-called "anchor line" in the many-multiplet method used in the search for a drift of the fine structure constant α in quasar absorption spectra[4]. We were able to improve the uncertainty in the linecenter by two orders of magnitude over previous measurements[5]. Together with a recent measurement[6] on Ca^+ this is the first absolute frequency measurement on a trapped ion in the weak binding limit and the first to demonstrate an accuracy of 1% of the linewidth in this regime. The latter is required e.g. for a planned experiment that aims at studying the $^{11}Be^+$ halo nucleus via isotope shift measurements[3].

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[6] A.L. Wolf *et al.* arXiv:0804.4130v2 (2008)

Observation of Coulomb crystals in a cryogenic linear octupole rf ion trap

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Large and small Coulomb crystals of laser-cooled Ca^+ ions have been observed in a cryogenic linear octupole rf ion trap. We have systematically investigated the changes of the shapes of the crystals by varying the axial static voltages and the asymmetric dc voltages (V_{dc}). For relatively small axial voltages, long prolate shapes of the ion crystals are observed when applying V_{dc}, while spherically symmetry shapes are observed for larger axial voltages (Fig.1). As shown in Fig.1 (a), even for a large number of ions the shell structures can be recognized inside the crystal. For a smaller number of ions (Fig.1 (b)), the shell structure is well resoved. The estimated interval between the shell structures is from 40 to 50 μm. Because of the small micromotion amplitudes in the large almost-field-free central region of the octupole ion trap, the clear shell structures are constructed. When a much larger number of ions are crystallized, the strange shape of the crystal emerges as shown in Fig.1 (c). Although the image is not clear, we recognize the dip along the axial direction. The reason of this property is possibly attributed to the characteristic sum potential in the radial direction[1].

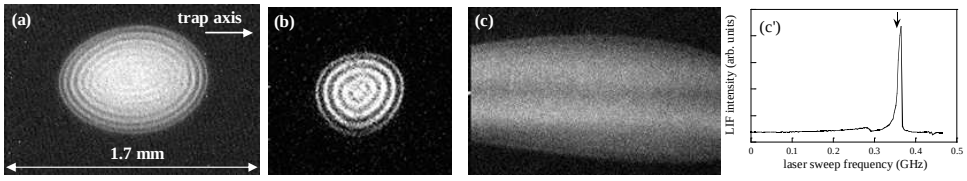

Figure 1: *Observed CCD images of the Coulomb crystals in the cryogenic linear octupole rf ion trap . The scale is same for the all images. The trapping parameters are* $f_{rf} = 6.04$ *MHz,* $V_{ac} = 157$ *V, and (a)* $V_{z0} = 1.90$ V, $V_{dc} = 0.09$ V, *(b)* $V_{z0} = 3.40$ V, $V_{dc} = 0.60$ V, *(c)* $V_{z0} = 0.80$ *V,* $V_{dc} = 0$ V *. The CCD image (c) was observed by setting the laser frequency to the position indicated by the arrow in the laser cooling spectrum of Fig.1 (c'). The number of ions are estimated to be (a)* $1{\times}10^3$*, (b)* $4{\times}10^2$*, and (c)* $> 2 \times 10^3$ *by assuming cylindrically symmetric crystals with a uniform number density of* $n_0 \sim 10^6$ *cm*$^{-3}$ *derived from the Coulomb crystals composed of a small number of ions.*

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Cryogenic planar elliptical ion traps for quantum simulation

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Quantum simulations have the potential to calculate interesting properties of many-body systems, such as the phase diagrams of spin systems, that are intractable using classical computers. It has been shown that such a simulation may be implemented using a system of trapped ions manipulated by laser radiation [1]. In particular, a 2-D array of ions would enable the observation of interesting effects such as spin frustration. In this work we discuss the design and construction of a planar elliptical rf ion trap [2] that is capable of confining stable 2-D arrays of ions. The trap is operated at 4K to take advantage of the strong suppression of motional heating at low temperatures [3]. We present calculations of the secular potential of the trap and the predicted structure of ion crystals therein, as well as the expected micromotion as a function of the number of ions. We discuss the fabrication of the trap and the experimental system, including trap potentials, apparatus for measuring ion heating rates, and steps toward quantum simulations.

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Quantum Information Processing with Ions and Photons

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We demonstrate the entanglement of two atomic ions separated by about one meter.[1,2] Ultrafast pulses are used to simultaneous excite two individual ytterbium ions confined in separate vacuum chambers, and the resulting single photons emitted are coupled into optical fibers and combined on a beamsplitter. Due to the quantum interference of photon pairs, a coincident detection of the photons heralds the entanglement of the two trapped ions.[3,4]

Proper choice of the excitation and detection scheme allows for entanglement between the atomic state of an ion and either the frequency or polarization of the emitted photon. Optical frequency qubits also allow for the implementation of a quantum gate that could be used for scalable quantum computation.[5] We demonstrate entanglement for both schemes, and in the latter case, full quantum state tomography of the ion-photon and ion-ion entangled systems, as well as violation of a Bell inequality. In future work, alternate decay channels in the ytterbium ion may be harnessed to produce infrared photons (even near telecom wavelengths) to enable long-distance quantum communication, and perhaps the implementation of a loophole-free Bell inequality measurement.[4]

While this photonic linking requires identical photons be entangled with the emitting sources, the subsequent quantum interference is independent of these sources. Thus, this scheme may also be extended to entangle hybrid quantum systems such as atoms and quantum dots, exploiting the advantages of each for applications in quantum information processing.

We acknowledge support from IARPA under ARO contract and the NSF Physics at the Information Frontier Program.

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Microfabricated segmented ion trap for scalable quantum information science

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Miniaturized multi-segmented ion traps are a promising architecture for quantum information science in a scalable way[1]. The microfabrication of linear Paul traps allows partitioning the trap in various storage and processing regions for a large number of qubits. The individual control of many qubits is fundamental for the implementation of large-scaled quantum algorithms. The crucial requirement for a scalable quantum processor is the fast qubit transport between spatial separated trap regions.
Numerical optimization of the trap geometry allows the effective suppression of non-harmonic contributions to the radial and axial potential in microfabricated linear traps. The trap optimization is discussed and the numerical modelling of ion shuttling is investigated in the adiabatic[2] and non-adiabatic regime[3]. The fast transport in a non-adiabatic regime is optimized using classical optimal control theory to avoid the excitation of vibrational quanta.
A novel scalable segmented linear microtrap with two different adjacent zones and 62 independently controlled electrodes allows shuttling of ions with numerically designed potentials at trap frequencies of a few MHz. The microtrap is characterized using sideband spectroscopy on the narrow $S_{1/2}$ to $D_{5/2}$ transition of the $^{40}Ca^{+}$ ion. Coherent Rabi rotations, Ramsey spectroscopy and optical ground state cooling are demonstrated and the heating rate is determined. The applicability of the microtrap for scalable quantum information science is proven[4].
The combination of sideband spectroscopy with a single ion transport along the trap axis at constant axial frequency is demonstrated: Initially Doppler cooled, the ion is shuttled to a different trap region where sideband spectroscopy is performed. Shuttled back, the ions quantum state is revealed from a fluorescence measurement. Such operations are necessary for subsequent two-qubit quantum logic operations.

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Individual ion addressing using a magnetic field gradient in a surface-electrode ion trap

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The ability to address individual ions is an important issue in using multiple trapped ions to perform quantum operations. Previous efforts have included using precisely focused laser beams aimed at only one ion at a time[1], which poses a significant technical challenge. An alternative is to use field-dependent transitions and a magnetic field gradient to shift the transition frequencies of ions as a function of position. This requires good stability of the local field in order to achieve desired fidelity of quantum operations. In a cryogenic Sr^+ ion trap we use the $5S_{1/2} \rightarrow 4D_{5/2}$ transition as an optical qubit, which can be Zeeman shifted using a bias field generated by external coils. We describe a scheme to create a local field gradient by integrating current sources onto a microfabricated surface-electrode trap, and present some initial experimental results. Taking advantage of the cryogenic environment, we also stabilize the field at the trap site using superconducting rings as flux shields. The rings can be integrated with the trap, simplifying implementation and improving alignment to the ions.

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Simulating a quantum magnet with trapped ions

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We can not translate quantum behaviour arising with superposition states or entanglement efficiently into the classical language of conventional computers[1]. A universal quantum computer could describe and help to understand complex quantum systems. But it is envisioned to become functional only within the next decade(s). A shortcut was proposed via simulating the quantum behaviour of interest in another quantum system, where all relevant parameters and interactions can be controlled and observables of interest detected sufficiently well[1]. Instead of translating quantum dynamics into an algorithm of stroboscopic quantum gate operations to run them on a universal quantum computer, we want to continuously control and manipulate the spins, equivalent to the way nature evolves the system of our interest.

Our system for a feasibility study is a linear chain of magnesium ions[2]. External fields and interactions between the ions are simulated/controled via rf- and laser-fields respectively. To initialize our system, we cool up to three ions close to the axial-motional ground state($\bar{n} \simeq 0.02$). To calibrate our operational fidelities, we implemented a geometric phase gate and prepared an entangled Bell state of two ions with a fidelity exceeding 95%. Subsequently, we were able to simulate an adiabatic evolution[3] of two spins described by the Quantum-Ising-Hamiltonian from paramagentic into (anti)ferromagnetic order with an fidelity of 98%. We proof that this transition is driven by quantum (not thermal) fluctuations providing us even an entangled state with a lower bound for the fidelity of 88%. We discuss these results and comment on the possibilities to increase the size of our system.
Already a comparably small amount of simulation-spins, of the order of 30-50, are supposed to be sufficient to outperform classical computers. In addition, the fidelities of the proposed operations are predicted to be sufficiently high in state of the art experiments and do not have to be performed within very demanding fault tolerant limits for universal quantum computation[2].

Based on new ion-trap technology it seems to become feasible to scale the ion simulator to a larger amount of ions to realize trap arrays, allowing to investigate quantum simulations on two dimensional spin-grids, e.g. spin-frustration. Experts in the field allow us to hope, starting from arrays spanned by 10x10 ions, to provide new insight into quantum dynamics. We expect/hope to observe effects that represent Quantum-Phase Transitions for many-particle systems.

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Coherence of the metastable qubit in $^{40}Ca^{+}$ ions

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We have been investigating the possibity of using the metastable $3\,^2D_{3/2}$ and $3\,^2D_{5/2}$ states in $^{40}Ca^{+}$ ions as a qubit.[1,2] These states are separated from each other by 1.82 THz. In this scheme they are connected with a stimulated Raman transition induced by two infrared lasers at 850 and 854 nm. The two lasers (a titanium sapphire laser and a taper-amplified diode laser) are phase-locked to each other by using a passive-type optical frequency comb.[3]

In this poster we present our recent study on coherence between the two metastable states. The decay of the off-diagonal density matrix elements between the metastable states are measured by using the Ramsey method. By combining a spin-echo π pulse in a Ramsey sequence, a visibility decay time of 5.1 ms is obtained. This is sufficient for implementing simple quantum gate sequences. This work is an essential step for realization of a qubit using the two metastable states, and, to the best of our knowledge, is the first demonstration of coherent manipulation of the internal states separated by around a THz using phase-locked lasers.

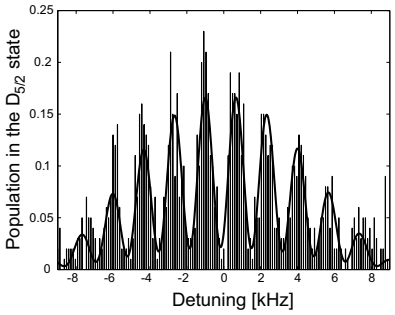

Figure 1: *Ramsey signal for the stimulated Raman transition between $3\,^2D_{3/2}$ and $3\,^2D_{5/2}$ states, taken with a pulse interval of 1 ms and a pulse duration of 98 μs.*

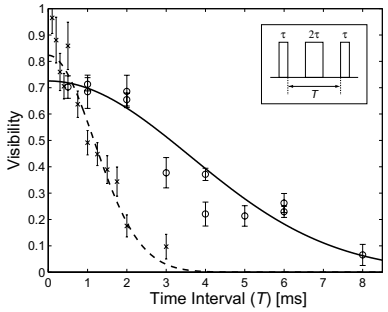

Figure 2: *Decay of the visibility of Ramsey signals. The circles represent visibility for spin-echo sequences, whereas the crosses represent visibility for normal sequences.*

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Robust creation of Dicke states of trapped ions by collective adiabatic passage

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We propose two novel techniques for the creation of maximally entangled symmetric Dicke states in a chain of trapped ions by using collective adiabatic passage. The techniques are applicable, with essentially the same level of complexity, to any number of ions and excitations. One of them [1] requires only a pair of chirped pulses from a single laser. By utilising a particular factorisation of the Hilbert space for multi-level ladders the problem is reduced to 'bow-tie' configuration energy-level crossings. By enforcing adiabatic evolution conditions, an arbitrary pre-determined collective Dicke state is created with high efficiency. This technique is naturally robust against fluctuations in the laser intensity and the chirp rate. This method may also be used to create number states of a collective vibrational mode of the ions. The other, closely related technique [2] uses global addressing of the entire chain by two pairs of delayed but partially overlapping laser pulses to engineer a collective adiabatic passage along a multi-ion dark state. This technique is a many-particle generalization of stimulated Raman adiabatic passage (STIRAP). It is therefore decoherence-free with respect to spontaneous emission and robust against moderate fluctuations in the experimental parameters. Because both techniques are very rapid, involving a single interaction step only, the effects of heating are almost negligible under realistic experimental conditions. We predict that the overall fidelity of synthesis of a Dicke state involving ten ions sharing two excitations should approach 98% with currently achievable experimental parameters.

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Coherent accumulation effects in the propagation of an ultrashort pulse train

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Absorbtion and dispersion can change the caracteristics of a resonant laser pulse propagating through an extended atomic medium. A weak ultrashort pulse (UP), whose temporal width is much shoter than the polarization decay time, is converted into an oscillatory function of time as it propagates[1]. When the medium is properly prepared by a preceding strong pulse, such a weak UP can experience amplification[2].

In this work we studied the propagation of an UP train through an extended collection of two- and three-level atoms (Figure 1). We worked in the weak field regime, with each individual pulse interacting with the medium in a perturbative way. Nevertheless, for repetitions periods shorter than the excited state lifetime, coherent accumulation of excitation between pulses will take place, and a strong excitation of the medium will occurs. Each pulse will find the medium in a different initial condition from that of the previous pulse. Thus, the pulse train propagation can't be described by linear dispersion law, and we solved the Maxwell-Bloch equations numerically.

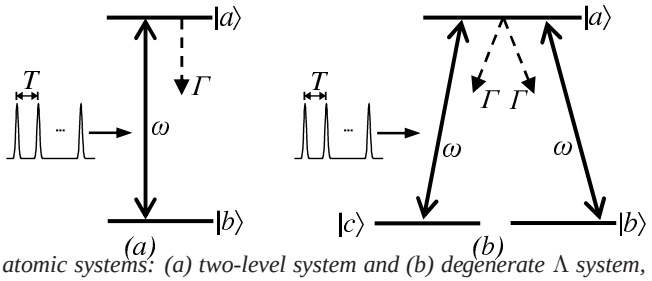

Figure 1: *The model atomic systems: (a) two-level system and (b) degenerate* Λ *system, interacting with a train of Gaussian UP with repetition period* T*. In both cases, the atoms are initially in their ground states.*

We observed that in the two-level system the pulse can experience both absorption and amplification. For the three-level configuration, after a large number of pulses, coherent accumulation by excitation of successives pulses leads to Electromagnetically Induced Transparency of the pulses and, at exit of the medium, the pulses have the same temporal shape than in the entrance of the atomic medium.

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Synthesis of Sub-Single-Cycle Optical Pulse Train with Constant Carrier-Envelope Phase

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[3]*Physics Department, National Taiwan University, Taiwan*
[4]*Institute of Electro-optical Engineering and Semiconductor Technology R&D Center, National Sun-Yat-Sen University, Taiwan*
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Molecular modulation is a process in which the coherence of a molecule is driven with two intense laser beams to its maximum value. The strongly driven molecular coherence in turn modulates the incident laser frequency to produce a broad spectrum constituting many sidebands.[1] When these sidebands are all in phase a train of ultrashort laser pulses can be produced. A four- wave mixing cross-correlation scheme can be used to determine the temporal width of these pulses.[2]
With the help of two independently tunable pulse- amplified single-mode lasers we have generated in room temperature H_2 collinearly propagating Raman sidebands that have wavelengths that range from 1203 nm in the infrared to deep in the vacuum ultraviolet. The frequencies covered by these sidebands span over 4 octaves for a total of more than 70000 cm^{-1} in the optical region of the spectrum.[3] In this paper we describe the synthesis of periodic waveforms consisting of a train of pulses that are 0.83 cycles long and have an electric field pulse width of 0.44 fs using a subset of the sidebands we generated in H_2.[4] The pulse envelope FWHM is 1.4 fs. The wavelength of the sidebands used is from 1203 nm to 301 nm. We verify by cross- correlation measurements using four-wave mixing in Xe the characteristic of these pulses and that their carrier- envelope phase is constant when the pulses are synthesized from commensurate sidebands. The estimated overall shift of the carrier-envelope phase is less than 0.18 cycles from the first to the last pulse of nearly 10^6 pulses in the pulse train. These pulses will be useful for probing phase-dependent quantum processes in atoms and molecules that will complement time-resolved studies such as photoemission of inner shell electrons and Auger decay that have recently been demonstrated by probing with few-cycle to single cycle soft-x-ray pulses.[5]

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2 M. Y. Shverdin et. al. Phys. Rev. Lett. **94**, 033904 (2005).

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Filamentation properties of air with carrier-envelope offset controlled, few cycle light pulses

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In this poster, we present work that explores the effects of filamentation as a function of the carrier-envelope phase for high power, few cycle light pulses. A filament is created when a high-powered optical field collapses due to the non-linear Kerr effect (self-focussing)[1]. The power density at this point is high enough to form a plasma in the air molecules through tunnel ionisation[2]. This alters the refractive index of the medium such that a stable equilibrium is obtained between self-focussing and self-defocussing which causes the length of the filament to exceed the Rayleigh length. The distance that self-focussing occurs at is dependent on the peak power of the pulse which, for a few cycle pulse, depends on the carrier-envelope phase. Within the filament many multi-photon ionisation events occur in the air molecules as well as self phase modulation, this results in a broad spectrum being observed at the end of the filament.

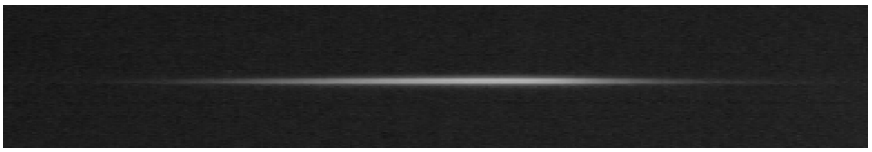

Figure 1: *A filament in air.*

We have observed filamentation in atmosphere using pulses generated by a Ti:Sapphire self mode-locked laser that is then intensified in a multi-pass amplifier and compressed in a neon filled hollow-core fiber. The laser system produces $<$6fs pulses with 0.4mJ energy and a spectral FWHM of 180nm at a central wavelength of 800nm. The carrier-envelope offset is controlled by using the f-2f interferometer technique that was devised by Hansch et al[3]. Experimental observations of changes to the properties of the filament, such as spectral broadening and the spatial onset, as a function of the carrier-envelope phase will be presented.

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Four-photon ionization of lithium.

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We consider a process of four-photon ionization of lithium under the action of a 25 fs pulse of the Ti:sapphire laser (photon energy $\omega = 1.56$ eV). Our interest in the problem stems from recent experiments on the intense laser field ionization of magneto-optically trapped (MOT) Li atoms [1]. In these experiments certain puzzling features in the photoelectron spectra were observed which we try to simulate with the help of a direct solution of the time dependent Schrödinger equation (TDSE). We describe the field-free lithium atom in the ground state by solving a set of self-consistent Hartree-Fock equations. We adopt the single active electron approach and describe the one-electron excitations from the valence $2s$ shell in the frozen-core Hartree-Fock (FCHF) approximation.

To solve the TDSE we follow the strategy similar to that we have applied before for two-electron systems [2]. The TDSE is solved for the time interval $(0, T_1)$ corresponding to the duration of the pulse. The spectrum of photoelectrons is obtained as $f(\mathbf{p}) = |\langle \mathbf{\Psi_p^-} | \mathbf{\Psi(T_1)} \rangle|^\mathbf{2}$, where $\Psi(T_1)$ is solution of TDSE at the moment of the end of the pulse, $\Psi_\mathbf{p}^-$ is a scattering state of lithium with asymptotic electron momentum $\mathbf{p}$. To construct this state we rely again on the FCHF approximation. The resulting photoelectron distributions (as functions of the component of the momentum $p_{||}$ along the EM field) are shown in Figure 1 for various peak strengths of the EM field.

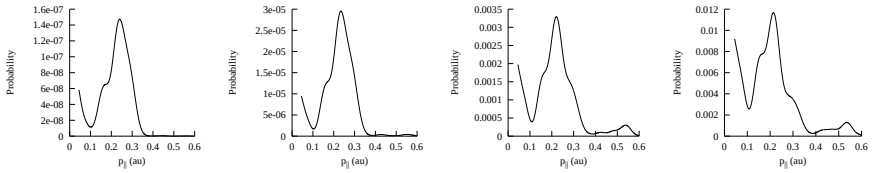

Figure 1: *Photoelectron momentum distribution as a function of $p_\parallel$ for various field strengths $F_{\rm AC} = 0.001; 0.002; 0.004; 0.005$ a.u.*

The prominent peak at about $p_{||} = 0.25$ a.u. in the electron distribution results from the 4-photon ionization of electrons from the ground state in the direction of the EM field. The presence of the central peak at $p_{||} = 0$ a.u. seemed puzzling in the experiment. Our results suggest, that considerable amount of photoelectrons may go in the direction perpendicular to the direction of the EM field, thereby creating central peaks in the distributions shown in the Figure 1.

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High harmonics generation from excited states of atomic lithium.

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We present a calculation of the harmonics yield from the lithium atom exposed to an intense 3.5 μm midinfrared laser pulse. Lithium atom is described in the framework of the Hartree-Fock approximation. Time dependent Schrödinger equation (TDSE) for Li atom in the presence of the laser pulse is solved using the procedure we have applied before for two-electron systems [1], [2]. The TDSE is solved for the time interval $(0, 30T)$, where T is duration of an optical cycle of the laser field. Our calculation shows that a considerable increase of the yield of high harmonics generation (HHG) can be achieved if initially the atom is prepared in an excited $2p$.

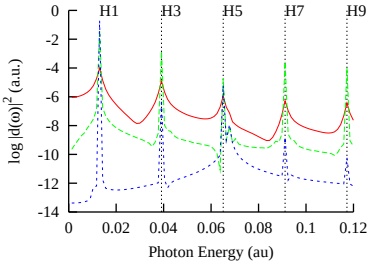

Figure 1: *Harmonics spectrum of Li from $2p$ state, peak strength of the EM field $F = 0.005$ a.u. (red) solid line, $F = 0.0025$ a.u. (green) long-dash line and from $2s$ state, $F = 0.005$ a.u. (blue) short-dash line.*

We show that this increase can be regarded as a resonant process due to appearance of a multiphoton resonance between the initial state and a quasienergy state. This conclusion follows from the approximative (neglecting depletion of the initial state) treatment of the HHG process using Floquet propagator for the description of the atomic evolution in presence of the laser pulse.

[1] I.A.Ivanov and A.S.Kheifets, Phys.Rev.A **74**, 042710 (2006)
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All-fiber, octave-spanning supercontinuum source for versatile wavelength selection and powerful 243nm source

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A light source was generated with spectrum spanning more than an octave (900-1950nm) using fiber processes. Sub-picosecond pulses at 1550nm are produced by a mode-locked fiber laser. The pulses are expanded to more than 20ps using dispersion compensating fiber (DCF) to reduce non-linearities in the amplification stage. The chirped pulses are amplified using an erbium-doped fiber amplifier to an average power of 800mW. The amplified pulses are then sent through highly non-linear fiber (HNLF) for supercontinuum generation.

Using a diffraction grating this light was dispersed and the wavelengths 1110nm and 1944nm were recollected with power density 20uW/nm and 10uW/nm respectively. The collected light is sufficiently bright for re-amplification by a simple fiber preamplifier, before the main amplification stage using a power amplifier. This light will then be recompressed to achieve high peak-power, sub-picosecond pulses. The 1944nm pulses will then be frequency doubled three times with approximately 20% total conversion efficiency to produce up to 1W of 243nm light. The 1110nm light will also be amplified and recompressed for use in an ion-trap experiment.

New tools for coherent control of light emission

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[3]*School of Mathematical Sciences, Tel Aviv University, Tel Aviv 69979, Israel*

Generation of coherent broadband UV emission by phase control of femtosecond multi-photon IR absorption was recently demonstrated.[1] The scheme is illustrated in Fig. 1: In atomic systems, rational phase shaping allows for rendering the intermediate two-photon resonance dark,[1,2] while optimizing the three-photon absorption which leads to the UV emission.
Our goal is to extend this scheme to molecules since more possibilities for control arise due to the internal degrees of freedom. Optimal Control Theory (OCT) will be employed where a state-dependant constraint [3] allows for suppressing population in a 'forbidden subspace'. In this formulation of OCT, an inhomogeneous Schrödinger equation is obtained. In order to solve it numerically, we derive a generalization of the Chebychev propagator. The formal solution of an inhomogeneous Schrödinger equation can be written in terms of functions of (known) operators acting on wavefunctions. Analogously to the case of the ordinary Schrödinger equation, the formal solution is amenable to polynomial approximations, using e.g. Chebychev polynomials. The propagator consists of the ordinary part plus an additional expansion in powers of the time step. We test the new propagator and present first applications.

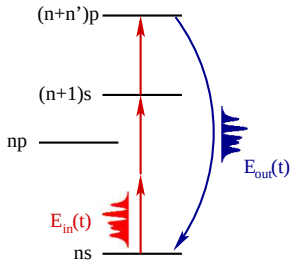

Figure 1: *Coherent broadband UV emission may be achieved by the absorption of three IR photons.*

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[2] D. Meshulach and Y. Silberberg, Nature **396**, 239 (1998).
[3] J. P. Palao, R. Kosloff and C. P. Koch, arXiv:0803.0921.

Ultrashort Pulse Generation with Zero Carrier Envelope Offset by using Broad Raman Sidebands

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Recently, it was shown that a pair of intense laser fields near-resonant to a Raman transition, could strongly drive the Raman coherence in a far-off resonant three-level system, preparing a superposition state of two quantum states with maximal coherence which results in generation of broad Raman sidebands. In this study, we focus on the potential application of Raman sidebands for ultrashort pulse generation. Such ultrashort pulses have advantages which are the ultrahigh pulse-repetition rate, the tunability of the center frequency, and the controllability of the carrier envelope offset (CEO). The repetition rate corresponds to the frequency spacing which is determined by the Raman transition frequency, typically exceeding a terahertz. The center frequency and the CEO can be tuned by precisely controlling the frequencies of the pump fields. If we can make monocycle pulses from such Raman sidebands with zero-CEO, all the pulses have the same carrier envelope phase and can potentially form an asymmetrically oscillating, intense nanosecond pulse, as illustrated in Fig. 1.

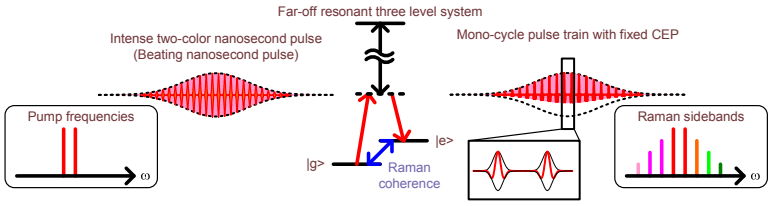

Figure 1: *Schematic of our procedure. Broad Raman sidebands with zero-CEO have a potential to form an intense, asymmetric nanosecond pulse.*

In this presentation, we show how we generate a broad sideband spectrum and control its CEO to zero. We drove a Raman coherence by using two intense nanosecond pulses generated from a dual-wavelength injection-lock pulsed Ti:Sa laser. We used pure-rotational Raman transition of $J = 0$ to 2 (10.6 Thz) in parahydrogen molecules at liquid nitrogen temperatures. The sideband spectrum can satisfy the zero-CEO condition when the two pumps were adjusted to have the appropriate frequencies. In order to broaden the sideband spectrum and measure the CEO, we further introduced a second harmonic (SH) of one of the two pump fields. Consequently, sidebands of over 50 components were generated, spanning from infrared to ultraviolet with the equidistant frequency spacing of 10.6 THz. We measured the CEO of less than 1 GHz by making use of the idea of the f-2f self-reference method. We will also show recent progress of spectral-phase compensation of the sidebands to give monocycle pulse train resulting in an asymmetric nanosecond pulse which has various potential applications in physical and chemical researches.

Orientation-Dependent Behavior of Strong-Field Ionization Rates for Laser-Irradiated Diatomics

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The strong-field process of above-threshold ionization (ATI) in laser-irradiated N_2, O_2 and F_2 molecules depending on molecular axis orientation with respect to incident laser field polarization is theoretically studied for various laser intensities. The incident laser intensity I is supposed to vary within a broad range corresponding to a large scale of the so-called Keldysh parameter γ extending between too small values $\gamma \ll 1$ (corresponding to tunneling regime of ionization) and too large values $\gamma \gg 1$ (corresponding to multiphoton regime of ionization).

The problem is addressed within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA) assuming the validity of *single-active electron* consideration and LCAO-MO method to model an initial molecular wavefunction as a set of one-electron molecular valence shells. Unlike alternative SFA-based consideration[1], the currently applied approach essentially exploits the *density functional theory* method of accurate composition of initial (laser-free) molecular state using the GAUSSIAN-03 code[2]. Such a composition allows to reproduce the correct ordering of at least three outer valence shells including the *highest-occupied molecular orbital* (HOMO) and provide accurate values of respective binding energy[3].

The resulting total molecular ionization rates were found to be very sensitive to spatial orientation of molecular axis with respect to incident laser field polarization. The form of such orientation-dependent behavior has been found to be mostly dependent on orbital and bonding symmetry of initial (laser-free) molecular state corresponding to HOMO. For example, the ionization rate calculated for N_2 (with $3\sigma_g$ HOMO) proved to have an orientation dependence quite different from that calculated for F_2 (with $1\pi_g$ HOMO). Meantime, the extent of how much pronounced the orientation dependence is for either of diatomics proved to be strongly dependent on incident laser intensity. Namely, the orientation dependencies of N_2 and F_2 ionization rates demonstrate a similar intensity-dependent behavior being most pronounced within the region of moderate laser intensity (viz., $\gamma \approx 1$ or $I \approx 2 \cdot 10^{14} W/cm^2$ for $\lambda = 800$ *nm*). Accordingly, these orientation dependencies become considerably less pronounced within either low-intensity (viz., $\gamma > 1$ or $I < 2 \cdot 10^{14} W/cm^2$) or high-intensity (viz., $\gamma < 1$ or $I > 2 \cdot 10^{14} W/cm^2$) domains. For the former intensity domain the behavior of revealed orientation dependencies confirms the respective earlier VG-SFA findings[1], whereas, for the latter domain, it rather agrees with opposite prediction of alternative MO-ADK calculations[4].

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[4] X. M. Tong, Z. X. Zhao, and C. D. Lin, Phys. Rev. A **66**, 033402 (2002).

On Contribution from Inner Molecular Shells to No Suppression in Strong-Field Ionization of F_2

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The highly multiphoton phenomenon of strong-field above-threshold ionization (ATI) in F_2 molecule is addressed within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA). Contrary to prediction[1], the total molecular ionization rate observed in experiments[2] for F_2 does not show a suppression as compared to its atomic counterpart Ar of nearly equal ionization potential. Unlike alternative VG-SFA consideration[1], the currently applied approach is essentially based on the *density functional theory* method of accurate numerical composition of initial (laser-free) molecular state using the GAUSSIAN-03 code[3]. Such a composition allows to reproduce the accurate binding energies of at least three outer valence shells including the *highest-occupied molecular orbital* (HOMO) using the model LB_α intramolecular binding potential, which incorporates both the *exchange* (factorized by α) and *correlation* (factorized by β) *LSDA*-potentials[4].

The resulting total ionization yields calculated for F_2 are well consistent with experiment and demonstrate no suppression versus Ar ionization. Moreover, the calculated partial contributions of ionization from separate inner molecular valence shells (such as $1\pi_u$ and $3\sigma_g$) suggest that predominant contribution to F_2 ionization is to be always from the $1\pi_g$ HOMO corresponding to the outermost valence shell. The latter is in a contradiction to alternative consideration[4] based on time-dependent density functional theory (TD-DFT), which attributed the mechanism of no suppression in F_2 ionization to an exceptionally enhanced ionization from $3\sigma_g$ inner shell, which may contribute comparably or even predominantly within the high-intensity laser field domain $I \geq 3 \cdot 10^{14} W/cm^2$. Such an interpretation seems to be at least insufficient leaving unexplained the reason, for which the relative contribution from similar $3\sigma_g$ inner shell in O_2 is to be always negligible that results in a high suppression observed[2] in ionization of O_2 versus its atomic counterpart Xe. Our present VG-SFA results assuming a predominant contribution from $1\pi_g$ ionization (similar to it occurs in O_2) thus suggest quite a different interpretation for no suppression in F_2 ionization. The phenomenon is presently explained by the closed-shell nature of $1\pi_g$ in F_2 implying a domination of the correlation *LSDA*-potential (viz., $\alpha = 0.988$ versus $\beta = 1$), in contrast to the open-shell $1\pi_g$ in O_2, to which the exchange *LSDA*-potential proved to contribute predominantly (viz., $\alpha = 1.745$ versus $\beta = 1$).

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Driven cold atoms as a model system for nonequilibrium dynamics : Dynamic phase transition

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Strongly driven nonlinear oscillators show a variety of interesting phenomena such as period doubling, bifurcation, chaos, and so on. Recently fluctuational paths in such nonequilibrium systems have revealed several distinct phenomena from those in equilibrium systems such as breaking of time-reversal symmetry[1] , lack of detailed balance[2], universal scaling laws in activation energies[3], etc. However these studies have been done so far in the systems having only single oscillator. Using cold atomic systems, we can study the effects of collective interactions on nonequilibrium systems. We previously investigated spontaneous breaking of population symmetry between identical attractors[4]. Here we further study its critical properties by measurements of relevant critical exponents. Obtained critical exponents reveals the long-range features of the phase transition and the interactions. In addition, by adding oscillating bias field, we observe new kinds of phase transition called dynamic phase transition[5].

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Femtosecond laser frequency comb for precision astrophysical spectroscopy

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Spectroscopy is a crucial tool for cosmology and the search for extrasolar planets. Broadband frequency combs have revolutionized precision spectroscopy in the laboratory with frequencies determined to better than one part in 10^{15}, good long-term stability and reproducibility. However, their application to astrophysics requires increasing the comb-line spacing by at least 10-fold from today's high repetition rate sources operating at about 1 GHz. We report the successful test of a 40-GHz comb generated from a 1-GHz source combined with a Fabry-Pérot cavity, without compromise on long-term stability, reproducibility and resolution. The application of this novel technique to astrophysics should allow more than a 10-fold improvement in Doppler-shift sensitivity, with significant impact to many fields, including the search for extrasolar Earths, the direct measurement of the universe expansion and the detection of the temporal variation of physical constants.

Photon localization and Dicke superradiance in atomic gases

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Photon propagation in a gas of N two-level atoms at rest, enclosed in a volume L^3, with a uniform density n, is studied using the effective Hamiltonian

$$H_e = \left(\hbar\omega_0 - i\frac{\hbar\Gamma_0}{2}\right) S_z + \frac{\hbar\Gamma_0}{2}\sum_{i\neq j} V_{ij} S_i^+ S_j^-$$

which describes photon mediated atomic dipolar interactions. $S_{i,z}^{\pm}$ are atomic operators. The density $P(\Gamma)$ of photon escape rates is determined from the spectrum of the $N \times N$ random matrix $\Gamma_{ij} = \sin(x_{ij})/x_{ij}$, where x_{ij} is the dimensionless random distance between any two atoms. The disorder strength is defined by the dimensionless parameter $W = \frac{\pi}{2}\frac{\lambda}{L}\frac{N}{N_\perp}$ where $N_\perp \equiv (k_0 L)^2/4$ is the number of transverse photon modes. A quantitative characterization of $P(\Gamma)$ is obtained using the function $C(L,W)$ defined between 0 and 1 by $C(L,W) = 1 - 2\int_1^\infty d\Gamma\ P(\Gamma)$. It measures the relative number of states having a vanishing escape rate. At finite size, we expect $C(L,W)$ to have a scaling form namely to be a function of $L/\xi(W)$ alone. We have verified this scaling behavior over a broad range of size and disorder when results are plotted as a function of $\pi^2 N/N_\perp$, see Fig. 1.

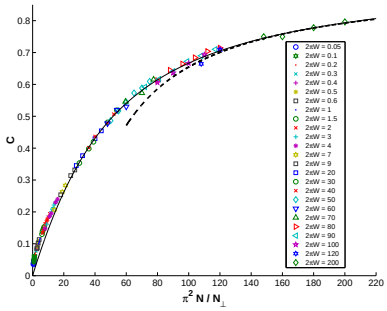

Figure 1: *Scaling behavior of $C(L,W)$ when plotted as a function of the parameter $\pi^2 N/N_\perp$. The continuous line is a fit obtained from a stochastic model and the dashed line results from microscopic calculations in the asymptotic limit $N \gg N_\perp$.*

We explain these results (see Fig. 1) using microscopic calculations together with a stochastic model which emphasizes the role of cooperative effects in photon localization and provides an interesting relation with statistical properties of "small world networks".

Motion-Induced Resonance: Toward a New Atom Manipulation Technique Using Periodic Structures

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Interactions of particles with periodic structures have been studied for a long time and used in various applications. Only a few are mentioned here: atomic beam diffraction techniques for surface analysis[1]; atom mirrors using periodically magnetized surfaces[2]. These applications are mostly concerned with the change or control of atomic motional states, but periodic structures can actually be used to induce resonance transitions of atomic internal states. We have been investigating this kind of resonance, with an aim of developing a new type of atom manipulation technique useful especially near surfaces. The experimental system we have used so far is Rb vapor confined in a thin cell to which a spatially periodic magnetic field is applied with an array of parallel current-carrying wires. Magnetic resonance transitions were induced by atomic motion through the periodic field, providing resonance spectra similar to ones obtained with the standard magnetic resonance technique[3]. Resonances induced by the combination of atomic motion and the temporal oscillation of the periodic field were also studied[4].

The above "prototype" experiments in a relatively simple setup using the thin cell of Rb vapor are now followed by ongoing experiments in more elaborate setups for investigating the change of the atomic momentum associated with the internal transition. Well controlled atomic beams in a vacuum, such as an atomic fountain of laser cooled atoms, interact with several types of periodic magnetic structures, for example, a stack of arrays of parallel current-carrying wires and a periodically magnetized transparent film enabling optical control of atoms as well. Resonance peaks much sharper than in the cell experiment have been obtained.

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Dressed Atom Formation by Periodic Crystal Fields

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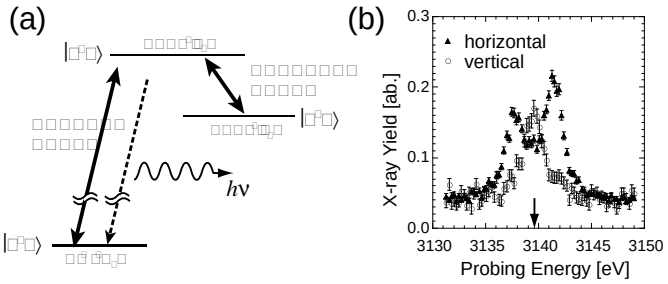
We investigated the coherent control of a quantum system by a periodic crystal field instead of a laser field. When fast ions propagate though a crystal, they experience a temporally-oscillating field originated from the periodic crystalline structure. As is the case for the photon irradiation, the crystal field induces the electronic transition of the ions at the resonant frequency. This unique process is called Okorokov effect or resonant coherent excitation (RCE). Since the oscillating field consists of numerous frequency components, a double resonance can be realized by adopting two of them simultaneously to the resonance. In three-dimensional RCE (3D-RCE)[1], two frequency components can be scanned independently by the tilt angles of the crystal θ and ϕ with respect to the ion velocity. We performed the two-color experiments on the three-level Λ system of helium-like Ar^{16+} ions. One frequency coupled $1s2p(2^1P)$-$1s2s(2^1S)$ and the other probed $1s^2(1^1S)$-$1s2p(2^1P)$ as illustrated in Fig. 1(a). In the present configuration, $|1^1S\rangle$-$|2^1P\rangle$ and $|2^1P\rangle$-$|2^1S\rangle$ are the electric dipole transition in the x-ray and vacuum ultra violet (VUV) energy region, respectively. Figure 1(b) shows the yields of x-ray emission from the Ar^{16+} ions to the horizontal and vertical directions which accompany the radiative decay of the probed states. In the horizontal direction, we observed a well resolved doublet around the transition energy of $|1^1S\rangle$-$|2^1P\rangle$ (3139.56 eV). This doublet is well-known as the Autler-Townes doublet which proves the strong, coherent interaction between the ions and the coupling field. Furthermore, we obtained a singlet peak in the vertical direction because the coupling field in the present experiment was linearly polarized in the vertical direction. Our result demonstrated that the internal state of traveling ions are coherently controlled by the periodic field on its way through the crystal.



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Negative Refractive Index Without Absorption

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we suggest a modified level scheme of excitons or polar molecules to study negative refractive index without absorption. We use quantum interference effects to suppress absorption and introduce chirality, and attempt to find optimal densities of media that will give us negative refractive index without absorption.

Decoherence in molecular wave packet through sub-Planck scale structure

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A phase space structure associated with sub-Planck scale ($<< \hbar$) can exist in non-local quantum superposition or Schrödinger cat states. Zurek[1] showed that appropriate superpositions of some of these states can lead to sub-Planck scale structures in phase space. These structures are very sensitive to decoherence. A cavity QED realization involving the mesoscopic superposition the so-called "compass states" has already given [2]. They have been also analyzed in the Kirkwood-Rihaczek representation [3] and in the form of entangled cat states [4]. Recently, the existence of those structures have been found in the time evolution of molecular wave packets [5]. Here, we study the effect of the decoherence due to the coupling with vibrational levels on these sub-Planck scale structures in molecular wave packets. The time evolution of these wave packets is investigated under the influence of an environment modeled, as usual, by a set of harmonic oscillators. We shall determine the master equation describing the reduced dynamics of the wave-packet and analyze the robustness of the sub-Planck structures against decoherence.

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Towards a Random Laser with Cold Atoms

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Since the Letokhov's seminal paper[1], random lasers have received increasing interest in the past decade. Random lasing occurs when the optical feedback due to multiple scattering in the gain medium itself is sufficiently strong to reach the lasing threshold. So far, it has been observed in a variety of systems[2], but many open questions remain to be investigated, for which better characterized samples would be highly valuable. A cloud of cold atoms could provide a promising alternative medium to study random lasing, allowing for a detailed understanding of the microscopic phenomena and a precise control on essential parameters such as particle density and scattering cross-section. We report our progress towards this goal.

As a first step, we have used a standard cavity to trigger laser oscillation with a magneto-optical trap (MOT) of rubidium 85 as gain medium. We present the realization of such a cold-atom laser, that we demonstrated with three different gain mechanisms, depending on the pumping scheme. By pumping near resonance, Mollow gain[3] is the dominant process and gives rise to a laser emission, whose spectrum is large (of the order of the atomic natural linewidth), whereas by pumping further from resonance, Raman gain between Zeeman sublevels produces a weaker, spectrally sharper laser[4]. At last, by using two counter-propagating pump beams, degenerate four-wave mixing (FWM) generates a laser with a power up to $300\ \mu$W. We have studied the main properties of these different lasers[5]. Mollow and Raman gains seem promising mechanisms for the search of random lasing in cold atoms, because they can produce high gain at frequency slightly detuned from the pump, allowing to distinguish between stimulated photons from the laser mode and elastically scattered photons from the pump beam. The FWM laser could find application in other fields, such as quantum optics, by making use of the correlation between the phase-conjugated waves.

As strong pumping reduces the atomic scattering cross-section, combining these gains with multiple scattering is a challenging problem. An independent measure of the scattering rate in presence of pumping should allow to evaluate the threshold of random lasing, which in our case will be a critical (on-resonance) optical depth for the cold atom cloud. We report the status of our current investigation on this question. Preliminary theoretical evaluation with Mollow gain seems to indicate that an optical depth of the order of 100 might be enough, which is reachable with the current state-of-the-art laser-cooling techniques.

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Laser Spectroscopy of Scandium Isotopes and Isomers

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Collinear laser spectroscopy experiments on the ScII transition 3d4s $^3D_2 \rightarrow$ 3d4p $^3F_3$ at $\lambda \approx 363.1$ nm were performed on the $^{42-46}Sc$ isotopic chain using an ion guide isotope separator with a cooler-buncher. The hyperfine structures and isotope shifts of five scandium isotopes (Z = 21) in the mass region $42 \leq A \leq 46$, with isomeric states in $^{44,45}Sc$, have been measured.[1,2]

Radioactive isotopes were produced in a fusion ion guide by irradiating a ^{45}Sc target in reactions of the type (d,p), (p,pxn), (p,p$'$) using 15 MeV deuterons and 25–48 MeV protons at 5-10 μA. Laser light was provided by a frequency-doubled Spectra-Physics 380D dye laser locked to a chosen molecular iodine absorption line.

The limits of possible variation of the mean squared charge radii in the scandium isotopic chains were deduced from measured isotope and isomer shifts. For the studied isotopes of the odd-Z element Scandium the magnetic dipole and electric quadrupole hyperfine coefficients A and B of both lower, 3d4s $^3D_2$, and upper, 3d4p $^3F_3$, states are obtained from the hyperfine structures using a χ^2 minimization fitting procedure. The results obtained from these data for the magnetic dipole and electric quadrupole moments of $^{43,44,44m,46}Sc$ isotopes are in good agreement with those summarised by Stone,[3] but has better accuracy. The nuclear moments $\mu(^{45m}Sc)$ and $Q_s(^{45m}Sc)$ are deduced for the first time. The unusually large quadrupole moment of the isomeric state of ^{45}Sc is the most striking feature of the present data.

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