Tuesday Posters

Two-Dimensional Localization of a Four-level Tripod-Type System in Laser Fields

Vladimir Ivanov[1,2], Yuri Rozhdestvensky[2], Kalle-Antti Suominen[1]

[1]*Turku Centre for Quantum Physics, Department of Physics and Astronomy, University of Turku, FIN-20014 Turku, Finland*
[2]*Saint Petersburg State University of Information Technologies, Mechanics and Optics, 197101 St. Petersburg, Russia*

During the last years, spatial localization of an atom using optical techniques has attracted extensive attention[1]. Possible applications of the atom localization range from the high-precision position measurement to the atomic nanolithography within the optical wavelength. While earlier proposed schemes include only 1D case, we propose a scheme for 2D subwavelength localization based on a four-level tripod configuration. Tripod schemes are experimentally accessible in metastable Ne, ^{87}Rb, and a number of other gases[2]. The atomic system couples with two optical standing waves propagating along perpendicular directions and with a probe laser field either of a running or of a standing wave. We have demonstrated the localization of an atom by measuring population in the upper state as well as in a ground state. The spatial distribution of the upper-state population forms such 2D periodic structures as spikes, craters and waves. In a special case of interaction, the similar spatial structures are found for population in one of ground states. Also, the atom observed in a ground state can be localized at the nodes of one of the standing waves.

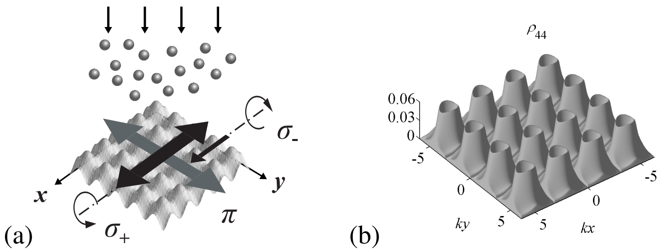


Figure 1: *(a) Atoms pass through an interaction range of coupling with two standing-wave laser fields and a probe laser field. The upper-level population ρ_{44} as a function of (kx, ky). The spatial distributions of the population represent such 2D periodic structures as (b) craters, spikes and waves.*

---

[1]E. Paspalakis, A. F. Terzis, and P. L. Knight, J. Mod. Opt. **52**, 1685 (2005).

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

Numerical Simulations on the Interferometry of Bose-Einstein Condensates in a Circular Waveguide

M.C. Kandes[1,2] and M.W.J. Bromley[1]

[1]*San Diego State University, San Diego, California, United States of America*
[2]*Claremont Graduate University, Claremont, California, United States of America*

Simple circular waveguides promise to be an ideal architecture for building high-precision matter-wave interferometers that exploit the coherent source of ultracold atoms provided by Bose-Einstein condensates. We present numerical simulations of gravity-induced quantum interference and Sagnac interferometry between counterpropagating condensate wave packets in a circular waveguide. Using finite difference methods to solve the time-dependent Gross-Pitaevskii equation, we investigate how the nonlinear, mean-field interaction of the condensates will impact the interferometric sensitivity and stability of these systems when operating under ideal conditions. In analyzing the observed interference patterns, we show that both the gravity-induced and Sagnac phase shifts can be reliably extracted from a set of reduced, one-dimensional interference patterns by using a Fourier-transform phase shift determination algorithm. The resulting phase shifts are then validated by comparison with simple analytic models.

Double-Well Interferometry on an Atomchip

M. Kuhnert, M. Gring, T. Langen, M. Schreitel, D.A. Smith, J. Schmiedmayer

Vienna University of Technology, Institute of Atomic and Subatomic Physics,Vienna, Austria

We present recent developments of a new atom chip experiment, built to study 1d quantum gases. We will show preliminary results of experiments involving contrast statistics for double-well interferometry.

Many-body quantum phenomena in atomic Bose-Josephson junctions

Chaohong Lee[1,2],

[1]*School of Physics and Engineering, Sun Yat-Sen University, Guangzhou 510275, China*
[2]*ACQAO and Nonlinear Physics Centre, Research School of Physics and Engineering, Australian National University, Canberra ACT 0200, Australia*

At nanokelvin temperatures, utilizing the well-developed techniques for cooling and trapping neutral atoms, atomic Bose-Einstein condensates have been demonstrated in several laboratories worldwide. Attribute to their long coherence time and high controllability, the quantum condensates of atoms provide an excellent opportunity for exploring quantum coherence, many-body quantum physics and non-equilibrium dynamics.

To detect and manipulate the quantum coherence of condensates, it is natural to couple different condensates via Josephson links. Under the mean-field coupled-mode theory, the macroscopic matter waves obey a series of coupled Gross-Pitaevskii equations. The nonlinear atom-atom interaction brings many novel nonlinear macroscopic quantum phenomena, such as, self-trapping [1], bifurcation [2], chaos [3], and nonlinearity-assisted tunneling [4]. In the full quantum treatment, the system obeys the Hubbard-like models and the many-body effects become significant for strong atom-atom interaction. We have predicted how coherent structures are destroyed by quantum fluctuations [5], propose how to prepare path-entangled states and then use them for high-precision measurement [6], and explore the resonant tunneling and interaction blockade induced by the competition between interaction and asymmetry [7].

For a many-body quantum system, symmetry breaking occurs if its mean-field state has no symmetry of its original many-body Hamiltonian. The symmetry breaking in atomic Bose-Einstein condensates has been discussed in several works [8]. However, the correspondence and breakdown between the mean-field and full quantum dynamics near a phase transition is still not clear. We investigate the dynamics of symmetry-breaking transitions in a Josephson coupled two-component condensate, obtain their universally dynamical mechanism, and explore the correspondence and breakdown between the mean-field and full quantum dynamics near a critical point [9]. The dynamical mechanism connects with the quantum adiabaticity, which may gain new insights into non-equilibrium quantum dynamics and adiabatic quantum computation.

---

[1]A. Smerzi et al., Phys. Rev. Lett. **79**, 4950 (1997).
[2]C. Lee et al., Phys. Rev. A **69**, 033611 (2004).
[3]C. Lee et al., Phys. Rev. A **64**, 053604 (2001); W. Hai et al., Phys. Rev. E **66**, 026202 (2002).
[4]C. Lee, E. A. Ostrovskaya, and Yu. S. Kivshar, J. Phys. B **40**, 4235 (2007).
[5]C. Lee, T. J. Alexander, and Yu. S. Kivshar, Phys. Rev. Lett. **97**, 180408 (2006).
[6]C. Lee, Phys. Rev. Lett. **97**, 150402 (2006).
[7]C. Lee, L. -B. Fu, and Yu. S. Kivshar, EPL **81**, 60006 (2008).
[8]M. Ueda et al., AIP Conf. Proc. **869**, 165 (2006).
[9]C. Lee, Phys. Rev. Lett. **102**, 070401 (2009).

Large Area Cold Atom Gyroscope

T. Lévèque, A. Gauguet, C. L. Garrido Alzar, F. Pereira Dos Santos, A. Landragin

LNE-SYRTE, Observatoire de Paris, CNRS, UPMC,
61 avenue de l'Observatoire, 75014 Paris, France
E-mail : thomas.leveque@obspm.fr

High precision atomic inertial sensors find scientific applications in the areas of general relativity, geodesy and in the field of navigation. We have realized and investigated the limit of a gyroscope based on cold atom interferometry[1]. In contrast with previous atomic setups, emphasis was placed on the long term stability and compactness of the device thanks to the use of laser cooled atoms. Moreover it has been designed to give access to all six axes of inertia[2] (the three components of acceleration and of rotation).

The sensitivity to acceleration is 5.5×10^{-7} m.s^{-2} at one second, limited by residual vibration on our isolation platform. Concerning the rotation, the sensitivity is 2.4×10^{-7} rad.s^{-1} at one second, at the level of the quantum projection noise due to the finite number of atoms. After 1000 seconds of integration time, we achieve a sensitivity of 1×10^{-8} rad.s^{-1}. We have studied in detail the different sources of systematic effect, which are mainly due to laser-atom interactions[1,3]. The main limit to the long term performances has been clearly identified to be linked to fluctuations of the atomic trajectories inducing Raman laser wave-front changes. Finally, the accuracy of our gyroscope has been characterized in term of bias and scaling factor.

A new experiment, based on a four pulse configuration[2] is now under study. It enables a huge increase of the area of the interferometer (by a factor 300 compared to the first one) leading to an enclosed area of 11 cm^2. Further increase of the area will benefit from more efficient Raman beam splitters, which have been recently demonstrated[4]. This new experiment should push the limits of such gyroscope and open new fields of application, as in geophysics for the study of the Earth rotation rate.

[1] A. Gauguet, *et al.*, "Characterization and limits of a cold atom Sagnac interferometer", Phys. Rev. A **80** 063604 (2009).

[2] B. Canuel, *et al.*, "Six-Axis Inertial Sensor Using Cold-Atom Interferometry", Phys. Rev. Lett. **97** 010402 (2006).

[3] A. Gauguet, *et al.*, "Off-resonant Raman transition impact in an atom interferometer", Phys. Rev. A **78** 043615 (2008).

[4] T. Lévèque, *et al.*, "Enhancing the Area of a Raman Atom Interferometer Using a Versatile Double-diffraction Technique", Phys. Rev. Lett. **103** 080405 (2009).

Advanced laser systems for coherent manipulation of matter waves in microgravity

W. Lewoczko-Adamczyk[1], M. Schiemengk[1], M. Krutzik[1] A. Peters[1,2] and the QUANTUS Collaboration[3,4,5,6,7,8]

[1]*Humboldt University of Berlin, Germany*
[2]*Ferdinand-Braun-Institut, Berlin, Germany*
[3]*Leibniz-University of Hannover, Germany*
[4]*Center of Applied Space Technologies and Microgravity (ZARM), Bremen, Germany*
[5]*University of Hamburg, Germany*
[6]*University of Ulm, Germany*
[7]*Technical University of Darmstadt, Germany*
[8]*University of Birmingham, England*

Targeting a long-term goal of studying cold quantum gases on a space platform, we perform preliminary experiments under microgravity conditions at the ZARM drop tower in Bremen. A sounding rocket mission is planned for the near future. In this context compact and robust laser systems have been developed.

This poster will present the laser system capable of performing dual-species atom interferometry experiments with degenerate Bose-Fermi mixtures of ^{87}Rb and ^{40}K at the drop tower. In particular, we show the concepts of a hybrid integrated master-oscillator power amplifier (MOPA) and a highly miniaturized, spectroscopy stabilized reference laser. The MOPA consists of a DFB laser chip, a tapered amplifier (TA), and micro-optical components, all integrated on a 10x50 mm^2 micro-bench. The reference laser combines this micro-bench technology with a mesoscopic vapor cell.

Two different concepts of Raman lasers for coherent manipulation of the wave packets will be shown in detail. The one is basing on a fiber electro-optical modulator (EOM) followed by injection lock of a DFB laser diode. The other one utilizes a double-passed acousto-optical modulator (AOM). Special challenges in the construction of this system are posed by the drop-tower environment which entails critical vibrations during drop capsule release and peak decelerations of up to 50 g during the launch of the catapult and during recapture at the bottom of the tower. All optical and electronic components have thus been designed with stringent demands on mechanical stability and reliability. These features of the laser system open new routes to quantum optics experiments also on other microgravity platforms, like ballistic rockets or the International Space Station (ISS).

This work has been done within the QUANTUS collaboration which is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50WM0835-0839

Variational Pair-Correlation Functions for Atomic Properties

S. Verdebout[1], P. Rynkun[2], P. Jönsson[3], G. Gaigalas[2], C. Froese Fischer[4], M.R. Godefroid[1]

[1]*Université Libre de Bruxelles, Brussels, Belgium*
[2]*Vilnius University Research Institute of Theoretical Physics and Astronomy, Lithuania*
[3]*Center for Technology Studies, Malmö University, Malmö, Sweden*
[4]*National Institute of Standards and Technology, Gaithersburg, USA*

It is possible to make good use of the variational method to target specific correlation effects in a many-electron system by tailoring the configuration expansion. In this line, the multiconfiguration Hartree-Fock method[1] (MCHF) is used to produce independent variational pair-correlation functions (PCFs), each one dedicated to a given electron pair. These nonorthogonal PCFs are coupled to each other by solving the generalised eigenvalue problem associated with a low dimension pair-correlation function interaction (PCFI) matrix. The Hamiltonian and overlap matrices are calculated using biorthonormal orbital transformations and efficient counter-transformations of the configuration interaction eigenvectors[2]. This methodology is shown to be efficient for the ground state energy of the beryllium atom[3]. In the present work, we investigate it for the $2s2p\ ^1P^o$ and $2s2p\ ^3P^o$ excited states, not only through the total energy convergence but also through the expectation values of the specific mass shift operator and the hyperfine structure parameters for measuring the impact of the mixing coefficient contraction.

The beryllium atom constitutes a perfect benchmark for the PCFI method since reference calculations based on complete active space expansions with a single common orthonormal basis remain possible to describe simultaneously all pair-correlation effects. For larger systems, it becomes hopeless to saturate a single orbital basis for describing different types of correlation contributing to the total energy, or different type of operators, and the PCFI approach should constitute an interesting alternative. The present study is supported by current developments of both the ATSP2K[1] and GRASP2K[4] packages.

[1]C. Froese Fischer et al., Com. Phys. Commun. 176, 559 (2007).
[2]J. Olsen et al., Phys. Rev. E 52, 4499 (1995).
[3]S. Verdebout et al., J. Phys. B: At. Mol. Opt. Phys. 43, 074017 (2010).
[4]P. Jönsson et al., Comp. Phys. Commun. 176, 597 (2007).

Fine-structure energy levels and lifetimes in Cr XII

G. P. Gupta[1], A. Z. Msezane[2]

[1]*Department of Physics, S. D. (Postgraduate) College, Muzaffarnagar - 251 001, (Affiliated to Chowdhary Charan Singh University, Meerut - 250 004), INDIA*
[2]*Department of Physics and Center for Theoretical Studies of Physical Systems, Clark Atlanta University, Atlanta, Georgia 30314, USA*

Excitation energies from ground states for 97 fine-structure levels as well as of oscillator strengths and radiative decay rates for all electric-dipole-allowed and intercombination transitions among the fine-structure levels of the terms belonging to the $(1s^22s^22p^6)3s^23p$, $3s3p^2$, $3s^23d$, $3p^3$, $3s3p3d$, $3p^23d$,$3s3d^2$, $3s^24s$, $3s^24p$, $3s^24d$, $3s^24f$, and $3s3p4s$ configurations of Al-like Chromium are calculated, using extensive configuration-interaction (CI) wave functions[1]. The important relativistic effects in intermediate coupling are included through the Breit-Pauli approximation via spin-orbit, spin-other-orbit, spin-spin, Darwin and mass correction terms[2]. In order to keep our calculated energy splittings as close as possible to the experimentally compiled energy values of the National Institute for standards and Technology (NIST), we have made small adjustments to the diagonal elements of the Hamiltonian matrices. In this calculation we have investigated the effects of electron correlations on our calculated data, particularly on the intercombination transitions, by including orbitals with up to n=5 quantum number. We considered up to three electron excitations from the valence electrons of the basic configurations and included a large number of configurations (1164) to ensure convergence[3].

Our calculated excitation energies, including their ordering, are in excellent agreement with the NIST values (wherever available). The mixing among several fine-structure levels is found to be very strong, with most of the strongly mixed levels belonging to the $(1s^22s^22p^6)3p^23d$ configuration. The mixing among the levels $3p^2(^1S)3d(^2D_{1.5})$ and $3p^2(^3P)3d(^2D_{1.5})$ is so strong that the level $3p^2(^1S)3d(^2D_{1.5})$ is designated by the eigenvector of the second largest magnitude[4]. We believe that our extensive calculations may assist the experimentalists in identifying these enormously mixed fine-structure levels uniquely. From our transition probabilities, we have also calculated radiative lifetimes of the fine-structure levels in Cr XII. Generally very good agreement between our calculated lifetimes and those from sophisticated calculation[5] are realized for many fine-structure levels. However, a few significant differences are noted and discussed. We predict new data for several levels where no other theoretical and/or experimental results are available.

[1]A. Hibbert, Comput. Phys. Commun. **9**, 141 (1975)
[2]R. Glass, A.Hibbert, Comput. Phys. Commun. **16**, 19 (1978)
[3]G. P. Gupta, A. Z. Msezane, Eur. Phys. J. **D49**, 157 (2008); Can. J. Phys. **87(8)**, 895 (2009)
[4]G. P. Gupta, K. M. Aggarwal, A. Z. Msezane, Phys. Rev. **A70**, 036501 (2004);K. M. Aggarwal, Vikas Tayal, G. P. Gupta, F. P. Keenan, Atom. Data Nucl. Data Tables **93**, 615 (2007)
[5]Froese Fisher et al., At. Data Nucl. Data Tables **92**, 607 (2006)

Dick effect and long term stability evaluation of HORACE compact cold atom clock

N. Rossetto, F. Chapelet, F.X. Esnault, R. Lambert, M. Lours, D. Holleville, N. Dimarcq

LNE-SYRTE, Observatoire de Paris, CNRS, UPMC,
61 avenue de l'Observatoire, 75014 Paris, France
E-mail : david.holleville@obspm.fr

HORACE is a compact cold caesium atom clock designed for onboard and space applications. Last year, stability as low as $2.2 \times 10^{-13}\tau^{-1/2}$ had been demonstrated at SYRTE, limited by atomic shot noise. Dick effect (i.e. noise due to the local oscillator used to generate the interrogation microwave signal) was negligible thanks to a very low phase noise sapphire cryogenic oscillator (SCO). Obviously this SCO is too voluminous to be used in an operational version of the HORACE clock.

This year, a compact and simple frequency synthesizer using an off the shelf quartz (10 MHz Wenzel Blue Top) has been realized and characterized at SYRTE. We will present the simulations leading to the identification of the commercial quartz matching with HORACE's requirements, and the architecture and the performances of the new synthesizer. We will also demonstrate that stability of HORACE clock operating with this synthesizer is just slightly degraded compared to this with SCO.

A lot of improvements have been made on the experiment to control thermal and magnetic environment of the clock. These improvements allow us to perform the long term evaluation and the study of systematic effects. We will present the main results concerning effects which depend on the atom density (collisional shift and cavity pulling), and give an error budget of HORACE clock and an estimation of its accuracy when it operates on ground. Expected performances in microgravity will be also presented.

AC Zeeman shifts in a trapped atom clock

V. Ivannikov[1,2], M. Egorov[1], S. J. Park[1], R. P. Anderson[1,3], B. V. Hall[1], A. I. Sidorov[1]

[1]*ACQAO and CAOUS, Swinburne University of Technology, Melbourne, Australia*
[2]*Institute of Physics, Saint Petersburg State University, Russia*
[3]*School of Physics, Monash University, Victoria 3800, Australia*

We report measurements of AC Zeeman shifts induced by magnetic dipole interactions using Ramsey spectroscopy of ultracold rubidium atoms. Atoms in a coherent superposition of states $|1\rangle$ and $|2\rangle$ (Fig. 1) are magnetically trapped on an atom chip and interrogated by excitation of the two-photon microwave-radiofrequency (MW-RF) transition with off-resonant intermediate state detuning. The transition $|1\rangle \leftrightarrow |2\rangle$ exhibits long coherence times[1] making it attractive for atom clock applications. To reduce the collisional shift the trapped ensemble is kept at 220 nK, 85 nK above the condensation temperature. Atoms are split coherently into the two states by a $\pi/2$-pulse with 2% accuracy. The MW or RF pulse applied during the free evolution time shifts the levels via magnetic dipole coupling, changing the frequency of the two-photon transition and the Ramsey fringe. The spin-echo technique is employed to suppress the level shifts that are independent of the coupling fields, including the residual collision shift. The field has constant amplitude and, if its duration is varied, gives a cosine interference fringe in $P_z(t) = \frac{N_1 - N_2}{N_1 + N_2}$, where N_1 and N_2 are the state populations. We measure the MW AC Zeeman shift to be 20.4 $\pm$0.5 Hz in the experiment with 250 000 atoms, 3.23 G trap bottom and 7 kHz MW Rabi-frequency. Preliminary results on RF-induced shifts range from 0.16 Hz to 3 Hz.

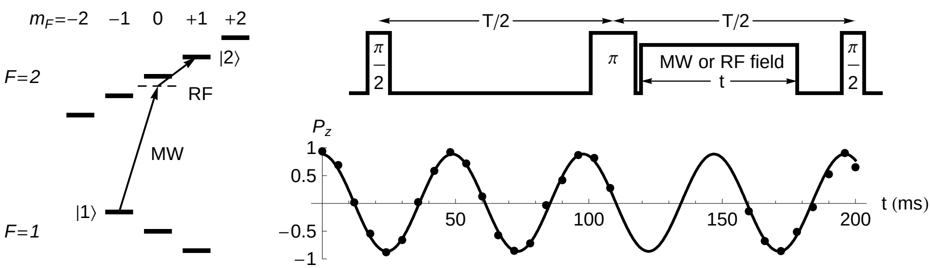


Figure 1: *(Left) Zeeman-split* ^{87}*Rb hyperfine ground-states, detuning from the intermediate level 1 MHz. (Top right) Ramsey spectroscopy sequence with spin-echo and a MW or RF perturbation. (Bottom right) Measured* $P_z(t)$ *(dots) fitted with a cosine (solid curve), T = 400 ms.*

[1]C. Deutsch *et al.*, "Spin self-rephasing and very long coherence times in a trapped atomic ensemble", arXiv:1003.5925 (2010).

Optoelectronic oscillator with an intra-loop Fabry-Perot cavity

Jang Myun Kim, D Cho

Korea University, Seoul, South Korea

We report construction and characterization of an optoelectronic oscillator (OEO), which includes a Fabry-Perot cavity as a part of the oscillator loop. The cavity provides strong mode selection by forcing the OEO to oscillate at its free spectral range and increases the Q factor by adding significant effective loop length. Frequency of the seed laser is stabilized to a cesium transition by modulation transfer spectroscopy and an acousto-optic modulator shifts the laser frequency to lock it to the cavity mode by the Pound-Drever-Hall technique. An electro-optic modulator generates sidebands at ± 3.6 GHz which are resonant with the cavity modes adjacent to the carrier mode. The phase difference between the carrier-sideband beat signals at upstream and downstream sides of the cavity is used to adjust the OEO loop length so that the OEO mode spacing is commensurate with the free spectral range of the cavity. Long term Allan deviation of the OEO is 6×10^{-8}. It represents 4×10^{-4} of the cavity linewidth.

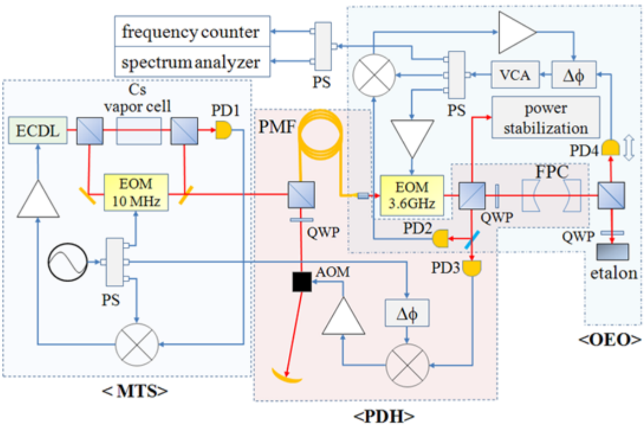


Figure 1: *(a) is OEO spectrum and (b) is allan deviation*

Towards an indium ion optical clock

Ying Li[1], Kensuke Matsubara[1], Tao Yang[2], Shigeo Nagano[1], Kazuhiro Hayasaka[1]

[1]*National Institute of Information and Communications Technology, Koganei, Tokyo 184-8795, Japan*
[2]*School of Opto-Electronics, Beijing Institute of Technology, Beijing 100081, China*

In recent years, optical frequency standards have shown dramatic improvements in stability and accuracy. A fractional frequency uncertainty of 8.6×10^{-18} has been demonstrated in an Al^+ optical clock using quantum logic spectroscopy. We are developing an optical frequency standard with a potential inaccuracy of 10^{-18} based on $^{115}In^+$. The $^1S_0$-$^3P_0$ transition at a frequency of 1267 THz (236.5 nm, natural linewidth of 0.8 Hz) serves as the clock transition.

The ultraviolet radiation is generated by two stages of frequency doubling of an amplified extended cavity diode laser (ECDL) at 946 nm. The ECDL is stabilized to an ultralow-expansion glass (ULE) reference cavity. A relative stability of 10^{-15} in one second is our goal of short-term stability. We have designed a vibration-insensitive Fabry-Perot cavity, and have estimated the elastic deformation of the cavity under the influence of a simulated gravity using finite element analysis package. The cavity made of ULE is designed as a long rectangular shape in the length of 150 mm. It is mounted on two $\Phi 5$ Viton rods attached to grooves on a flat plate. The contacting width of the cavity on each of the rods is assumed to be about 0.5mm. The Airy point at the position of the support is numerically calculated. When acceleration of 9.8 m/s^2 in the vertical direction is added to this cavity, the change of the length between the centers of two mirrors is estimated to be less than 10^{-12} m. This novel cavity has been fabricated. The designed finesse is higher than 250,000, and thermal noise level is expected to be in the order of 10^{-16}.

The original idea of the single-ion clock assumes the use of $^1S_0$-$^1P_1$ transition at 159 nm for laser cooling as well as for state detection. Due to the difficulty in generating the single-mode coherent radiation at vacuum ultraviolet (VUV) region an alternative approach to use $^1S_0$-$^3P_1$ at 230nm has been deployed previously. We will employ a different approach, in which an $^{115}In^+$ ion in the Lamb-Dicke regime is prepared by sympathetic cooling by another ion. The state detection on the ion is made either by use of single-mode 230 nm light, quantum logic spectroscopy or possibly multi-mode VUV radiation at 159 nm.

We have chosen $^{40}Ca^+$ as the refrigerator ion, because we have lots of experience of cooling and trapping. Furthermore, we have developed a single $^{40}Ca^+$ optical clock with a frequency inaccuracy of 10^{-14}, resulting in one of the CIPM mise en pratique list of recommended radiations. In the Ca^+ optical clock all the relevant transitions are accessible with laser diodes (LDs). The $^{40}Ca^+$ clock laser been stabilized to a linewidth of about 3 Hz. A typical long-term frequency drift is about 0.03 Hz / s. The Allan deviation is smaller than 5×10^{-15} at an averaging time of 1s ˜10s. The stability is enough for sideband cooling of the $^{40}Ca^+$ - $^{115}In^+$ system as well as for quantum logic spectroscopy.

A dipole lattice trap for mercury: pathway to a new optical clock.

S. Mejri, L. Yi, J. J McFerran, S. Bize

LNE-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France

Ion based frequency references have been leading the way in terms of line-centre accuracy[1]. Some neutral atom based clocks have the potential of reaching similar levels of accuracy with less integration time, due to the higher number of quantum absorbers. Optical lattice clocks based on neutral atoms are predicted to produce an accuracy in the range of 10^{-17}. Optical lattice clock using strontium atoms has demonstrated an uncertainty at the 10^{-16} level[2]. At this level, the blackbody radiation shift is the largest correction and the largest contribution to the strontium clock uncertainty.

Due to its low sensitivity to blackbody radiation a mercury atom standard has the potential to achieve an fractional frequency uncertainty at the range 10^{-18}.

After achieving magneto-optic trapping (MOT) of mercury[3] and after preliminary measurement of the clock absolute frequency on laser-cooled free falling atoms[3], we will report our efforts to develop a dipole lattice trap suitable for a mercury optical lattice clock. Several challenges have to be met due to the wavelength range and the uncertainty in the predicted value of the magic wavelength. We will report our measurements of the MOT parameters (temperature, cloud size)[4], as well as the implementation of a low noise detection system for atoms confined to lattice trap with light near the predicted magic wavelength; we provide data indicating the first trapping of neutral mercury atoms in 1D dipole lattice trap[5]; this loading of the trap needs further augmentation so we can determine, experimentally the magic wavelength and perform the spectroscopy of the clock transition in the Lamb-Dicke regime.

[1]T. Rosenband et al., Science 319, 1808 (2008) .
[2]A. D. Ludlow et al., Science 319, 1805 (2008).
[3]M. Petersen et al., Phys. Rev. Lett. 101, 183004 (2008)
[4]J.J.McFerran et al. submitted to Opt. Lett
[5]S. Mejri et al. EFTF proceedings, Noordwijk, Netherlands (2010).

Using $(\Delta F = 1, \Delta m_F = \pm 1)$ transitions as a diagnostic tool for atomic fountain clocks

N. Nemitz, V. Gerginov, S. Weyers, R. Wynands

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

While investigating the feasibility of a precision measurement of the caesium g-factor ratio using PTB's fountain clocks CSF1 and CSF2[1], we noticed substantial, unexpected asymmetries in the transition probability spectra of the $(\Delta F = 1, \Delta m_F = \pm 1)$ transitions.

Our analysis shows that the shape of the spectra is consistent with the presence of an unintended angle between the magnetic quantization field and the vertical axis of the fountain's microwave cavity. The resulting mixing of vertical and horizontal RF field components in the atomic frame of reference breaks the normal rotational symmetry of the TEM011 mode. Especially the $\Delta m_F = \pm 1$ transitions then become sensitive to the horizontal position of the atoms during the cavity passage.

A simulation based on the Bloch equations in a co-rotating frame of reference recreates the observed spectra with very few free parameters: Only the position of cavity passage, tilt of the quantization field and a small difference between the magnetic field amplitude in the cavity compared to that averaged over the entire trajectory are required.

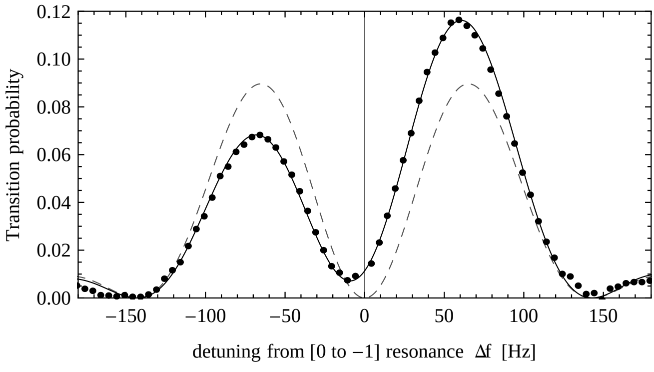


Figure 1: *Transition probability spectrum of the* $|F = 3, m_F = 0\rangle$ *to* $|F = 4, m_F = -1\rangle$ *transition for a single cavity passage at an elevated microwave amplitude corresponding to a* $\frac{5}{2}\pi$ *pulse for the* $|F = 3, m_F = 0\rangle$ *to* $|F = 4, m_F = 0\rangle$ *clock transition. Comparison of measurements (circles) to simulations with quantization field tilt of 0° (gray, dashed line) and 4° (black line).*

We hope that the analysis of the $\Delta m_F = \pm 1$ spectra can be developed into a useful diagnostic for the position of the atomic cloud in the resonator itself. This would be helpful for optimizing fountain alignment and launch direction, as well as putting stricter limits on the contribution of cavity phase gradients on the error budget for clock operation[2].

[1] Nemitz et al., Proceedings of the 24th European Frequency and Time Forum (EFTF), 2010 (in print)
[2] See for example section on cavity phase shifts in Weyers et al., Metrologia 38 (2001) p. 343ff .

New Prospects for Optical Lattice Clocks Based on Ultracold Alkaline-Earth-Like atoms

V.D. Ovsiannikov[1], V.G. Pal'chikov[2], A.V. Taichenachev[3], A.V. Yudin[3], N.A. Dugin[4], H. Katori[5], M. Takamoto[5]

[1]*Voronezh State University, Voronezh, Russia*
[2]*National Research Institute for Physical-Technical and Radiotechnical Measurements, Moscow Region, Russia*
[3]*Institute of Laser Physics, Novosibirsk, Russia*
[4]*Radiophysical Researh Institute, Nizhniy Novgorod,Russia*
[5]*Department of Applied Physics, School of Engineering, the University of Tokyo, Tokyo, Japan*

In this paper, we systematically evaluate various sources of uncertainty for the alkaline-earth optical lattice clock either on odd isotopes or on even isotopes[1,2,3] and argue that an accuracy of better 10^{-18} is attainable, which is competitive with that of the best ion clock with Al+[4].

In the first part of the paper we propose an accurate optical lattice clocks based on Hg atoms and evaluate the uncertainty of this optical lattice clock by carrying out higher-order calculations of the relevant atomic properties (ac polarizabilities and hyper-polarizabilities, two-photon ionization rate, black-body radiation shift, etc). As a result, we have shown that Hg atom is a promising candidate for highly accurate optical lattice clocks with an estimated uncertainty of less than 10^{-18}. In the second part of the paper we investigate an influence of the localization effects on the light shifts of the clock transition frequency, taking into account the magneto-dipole and quadrupole contributions. In particular, it is shown that in the Lamb-Dicke regime the dependence of this shift on the lattice laser intensity I has the following form

$$\Delta\omega_{clock} = \alpha(\omega)I + \beta(\omega)\sqrt{I} + \gamma(\omega)I^2 \tag{1}$$

where ω is the frequency of the lattice field, $\alpha(\omega)$ is the difference of polarizabilities and $\gamma(\omega)$ is the difference for the hyperpolarizabilities. At the magic frequency ω_m the coefficient $\alpha(\omega)$ is exactly zero, while the coefficient $\beta(\omega) \neq 0$. Therefore, due to this reason, depending equation (1) on the value $\beta(\omega)$ can have a principal significance for frequency standards from metrological point of view[5,6]. Numerical estimations are presented here.

[1]H. Katori, M. Takamoto, V.G. Pal'chikov et al, Phys.Rev.Lett. 91, 173005 (2003).
[2]A.V. Taichenachev, V.I. Yudin, C.W. Oates et al, Phys.Rev.Lett. 96, 083001 (2006).
[3]V.D.Ovsiannikov,V.G.Pal'chikov,A.V.Taichenachev et al, Phys.Rev.A 75, 020501(R) (2007).
[4]T. Rosenband, D.B. Hume, et al., Science 319, 1808 (2008).
[5]A.V. Taichenachev, V.I. Yudin, V.D. Ovsiannikov et al. Phys.Rev.Lett. 101, 193601 (2008).
[6]H. Katori, M. Takamoto, S.I. Marmo et al, Phys.Rev.Lett. 102, 063002 (2009).

Research on optical clock with ytterbium atoms trapped in optical lattice

Chang Yong Park[1], Won-Kyu Lee[1], Dai-Hyuk Yu[1], EOK-Bong Kim[2], Sun Kyung Lee[3]

[1]*Korea Research Institute of Standards and Science, Daejeon, Korea*
[2]*KAIST, Daejeon, Korea*
[3]*Queen's University, Belfast, United Kingdom*

We built an optical clock system referenced to ytterbium optical lattice[123]. The preparation of ytterbium sample in optical lattice starts from gathering a number of isotope-selected cold atoms with magneto-optical trapping (MOT)with $6s6p(^1S_0 -^1 P_1)$ transition (399 nm). We developed 399 nm laser diode systems whose frequency were locked with spectroscopy on a collimated atomic beam. Because the temperature of blue MOT (about 1 mK) is higher than the potential depth of optical lattice generated with 1 W of Ti-sapphire laser, a second stage MOT(green MOT) with the $6s6p(^1S_0 -^3 P_1)$ transition (556 nm) was performed, by which the temperature of atoms dropped below 50 μK. 556 nm laser was obtained from frequency doubling of 1112 nm diode laser amplified with Yb-doped fiber amplifier and MgO-doped wave guided periodic poled Lithium Niobate (WG-ppLN). For efficient transfer the atoms in each step (blue MOT - green MOT - optical lattice), we controled the laser frequency and power and magnetic field gradient adequately.

Ultra-narrow linewidth probe laser for precision spectroscopy of clock transition of ytterbium atoms was developed. The linewidth was narrowed with a super-cavity enclosed by vacuum chamber and 3-folded thermal radiation shields. The temperature of outer shield was stabilized actively by thermo-electric cooler. The probe laser was aligned to co-propagate with optical lattice laser with caution to avoid doppler shift and the center frequency of the probe laser scanned by acousto-optic modulator and computerized control. The interaction time of probe laser and atoms is controled with a precise pulse generator triggered by computer command.

Another 399 nm diode laser system was built to be used in measuring population of atoms remaining in the state of $^1S_0$ after applying Rabi or Ramsey spectroscopy by the probe laser. Also we developed the several diode laser systems whose frequency were tuned to $6s6p^3P_0 - 6s7s^3S_1$(649 nm) and $6s6p^3P_2 - 6s7s^3S_1$(770 nm) transition to optically pump atoms in $^3P_0$ state to $^1S_0$ state. The frequencies of the laser system were locked to the fluorescence signal from a well collimated thermal atomic beam pumped by two photon procedure to $6s6p^3P_0$ and $6s6p^3P_2$ state.

We are on the state of measuring clock transition. With this work we expect the optical clock with accuracy of 10^{-14} level.

---

[1]Z.W. Barber,* C.W. Hoyt, C.W. Oates, and L. Hollberg, "Direct Excitation of the Forbidden Clock Transition in Neutral 174Yb Atoms Confined to an Optical Lattice",PRL 96, 083002 (2006)

[2]Takuya Kohno, Masami Yasuda, Kazumoto Hosaka, Hajime Inaba,Yoshiaki Nakajima, and Feng-Lei Hong,"One-Dimensional Optical Lattice Clock with a Fermionic 171Yb Isotope",Applied Physics Express 2 072501(2009)

[3]N. D. Lemke, A. D. Ludlow, Z.W. Barber, T. M. Fortier, S.A. Diddams, Y. Jiang, S. R. Jefferts, T. P. Heavner, T. E. Parker, and C.W. Oates,"Spin-1=2 Optical Lattice Clock",PRL 103, 063001 (2009)

Laser spectroscopy of forbidden transitions in trapped ions: from electronic to nuclear

E. Peik, O.A. Herrera Sancho, N. Huntemann, B. Lipphardt, M. Okhapkin, I. Sherstov, Chr. Tamm, K. Zimmermann

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Optical frequency standards based on forbidden transitions of trapped and laser-cooled ions allow to achieve high stability and accuracy. We present results on the spectroscopy of the electric octupole transition $^2S_{1/2}(F=0) \to {}^2F_{7/2}(F=3)$ of a single trapped laser-cooled $^{171}\mathrm{Yb}^+$ ion. This transition is of interest as an optical frequency standard because of its extremely small natural linewidth in the nHz range. We developed a frequency-doubled diode-laser system at 467 nm to excite the octupole transition and observe spectra with a resonant excitation probability of about 65 % and an essentially Fourier transform-limited resolution of 13 Hz[1]. The strong dependence of the transition frequency on the value of the fine structure constant α suggests longterm comparison with other optical frequency standards, especially the $^2S_{1/2} \to {}^2D_{3/2}$ electric quadrupole transition[2] in $^{171}\mathrm{Yb}^+$, in order to test the constancy of α.

A nuclear excitation at about 7.6 eV in the ^{229}Th nucleus may provide a reference transition that is highly immune to field-induced systematic frequency shifts[3,4]. We are preparing nuclear laser spectroscopy of this resonance in trapped thorium ions. About 10^5 Th^+ ions are stored in a linear ion trap. Helium buffer gas is used for collisional cooling and quenching of low lying metastable levels. Cyclic laser excitation of several electronic resonance transitions around 400 nm wavelength has been observed. In Th^+, the nuclear transition rate should be strongly enhanced by the interaction of the nucleus with the electron shell. Concepts for a highly accurate nuclear clock based on ^{229}Th and the first steps towards the experimental realization will be described.

This work was supported by a grant from the Foundational Questions Institute FQXi and by DFG through SFB 407 and QUEST. O.A.H.S acknowledges support from TEC and DAAD.

[1] I. Sherstov, M. Okhapkin, B. Lipphardt, Chr. Tamm, E. Peik, Phys. Rev. A **81**, 021805(R) (2010)

[2] Chr. Tamm, S. Weyers, B. Lipphardt, E. Peik, Phys. Rev. A **80**, 043403 (2009)

[3] E. Peik, Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

[4] E. Peik, K. Zimmermann, M. Okhapkin, Chr. Tamm, in: Proceedings of the 7th Symposium on Frequency Standards and Metrology, Ed.: L. Maleki, World Scientific, Singapore, 2009, p. 532-538; arXiv:0812.3458

Non-Linear Spectroscopy of Rubidium in Hollow Core Fibres For Compact Clocks and Quantum Optics

C. Perrella[1], P.S. Light[1], F. Benabid[2], T.M. Stace[3], A.N. Luiten[1]

[1]*University of Western Australia, Crawley, Western Australia, Australia*
[2]*University of Bath, Claverton Down, Bath, England*
[3]*University of Queensland, Brisbane, Queensland, Australia*

The new technology of Hollow Core Photonic Crystal Fibres (HC-PCF) allows for an atomic vapour to interact strongly with high intensity light over long lengths. We are using this property to efficiently drive the Rubidium non-linear, two photon, 778nm 5S to 5D transition within such a fibre. This particular arrangement can potentially drive this transition strongly enough to see over 50% absorption of the driving laser, compared with the traditional bulk cell technique that scatters only 10^{-6} of incident power. This gives an excellent signal to noise ratio for creating a compact and robust atomic clock. Furthermore, we are also considering this extreme nonlinearity for various quantum information applications such as creating photon number resolving filters or new types of deterministic gates in the linear optics regime.

Current experiments using 35μm core Kagome HC-PCF, provided by the University of Bath, have achieved a Rubidium fill length of over 30mm. This has allowed preliminary investigation of the 778nm 5S to 5D transition within the fibre. Initial characterisation of the transition within the fibre, has enabled prediction of potential clock frequency stability of 1×10^{-14} in 1 second integration times. The stability is limit by AC Stark shifts of the transition caused by the power fluctuations associated with fluctuating in-coupling to the fibre. Strong AC Stark shifts have been observed on the 780nm Rubidium D2 line in the presence of a far detuned ($>$ 10GHz) laser: ground state shifts up to 200MHz have been observed, which equates to a 10mK potential that is created by the detuned laser. Coupled with these shifts, the optical depth of the fibre has been observed to change by more than 1% due to attractive and repulsive forces induced by this potential. This observation suggests that even with only 10mW of in-coupled detuned power we can weakly guide room-temperature atoms within the fibre. This guide can potentially reduce atom-wall collision rates which would greatly benefit both the clock and quantum information experiments.

Another avenue of research that has been explored is Light Induced Atomic Desorption (LIAD) in which a strong laser is able to eject atoms off the wall of the fibre. The optical depth of the Rubidium vapour inside the fibre has been observed to increase by more than a factor of 3 in response to 10mW of in-coupled infrared light. A state of heightened optical depth can be sustained for up to 1.5 hours by which time the depth has exponentially decreased back to its normal state. A model of LIAD's temporal behaviour has been developed which show these experimental observations. The LIAD effect is of great benefit for both applications in atomic clocks and quantum optics.

Radiofrequency dressing of multiple Feshbach resonances

A. M. Kaufman[1], R. P. Anderson[1,2], T. M. Hanna[3], E. Tiesinga[3], P. S. Julienne[3], D. S. Hall[1]

[1]*Department of Physics, Amherst College, Amherst, MA 01002-5000, USA*
[2]*ARC Centre of Excellence for Quantum-Atom Optics and Ultrafast Spectroscopy, Hawthorn, Victoria 3122, Australia*
[3]*Joint Quantum Institute, NIST and University of Maryland, 100 Bureau Drive, Stop 8423, Gaithersburg, Maryland 20899-8423, USA*

We investigate using magnetic and radiofrequency (RF) fields to provide rapid, precise control of atomic interactions. Colliding atoms in different hyperfine ground states of ^{87}Rb exhibit a cluster of Feshbach resonances at both 9 G and 18 G. These resonances yield a rich scattering landscape when an RF field is applied (Fig. 1). We provide a quantitatively accurate picture to explain our data,[1] in which RF-dressed bound states interact with the entrance channel. We demonstrate that the tunability typically achieved with magnetic fields can be augmented with an RF field, thereby expanding and refining the experimental toolbox for controlling atomic interactions.

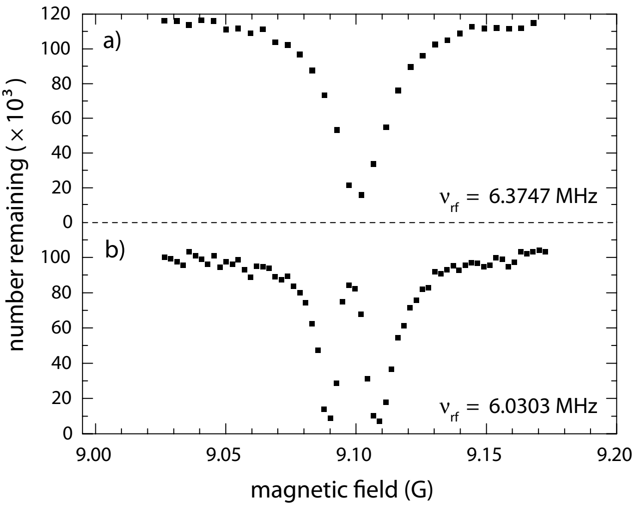


Figure 1: *Illustration of RF-dressed Feshbach resonances. a) The RF field is far-detuned from a bound state resonance, and atomic loss occurs when the entrance channel couples to an undressed bound state. b) The RF field is resonant with a pair of bound states. The resulting dressed states each couple to the entrance channel for a particular range of magnetic field, yielding a feature analogous to an Autler-Townes doublet.*

[1]A. M. Kaufman, R. P. Anderson, T. M. Hanna, E. Tiesinga, P. S. Julienne, D. S. Hall, Radiofrequency dressing of multiple Feshbach resonances, *Phys. Rev. A* **80**, 050701 (2009).

Resonant scattering effect in spectroscopies of interacting atomic gases

J. J. Kinnunen

Department of Applied Physics, Aalto Univeristy, Finland

We consider spectroscopies of strongly interacting atomic gases, and we propose a model for describing the coupling between quasiparticles and gapless phonon-like modes. Our model explains features in a wide range of different experiments in both fermionic and bosonic atomic gases in various spectroscopic methods.

Polarized alkali vapor with minute-long transverse spin-relaxation time

M.V. Balabas[1], T. Karaulanov[2], M.P. Ledbetter[2], D. Budker[2,3]

[1]*S. I. Vavilov State Optical Institute, St. Petersburg, 199034 Russia*
[2]*Department of Physics, University of California at Berkeley, Berkeley, CA 94720*
[3]*Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley CA 94720*

Long-lived ground-state coherences in atomic vapor cells form the basis for atomic clocks[1], atomic magnetometers[2], quantum memory[3], spin-squeezing and quantum non-demolition measurements[4,5], and precision measurements of fundamental symmetries[6]. We report[7] spin coherence lifetimes in excess of 60 seconds in a 3 cm diameter, buffer-gas-free cell (see Fig. 1), corresponding to approximately 10^6 polarization preserving alkali-wall collisions. Such long lifetimes are enabled by a combination of 1) an alkene based wall-coating material, 2) a locking stem to inhibit alkali atoms from colliding with the cell reservoir, 3) operation in the spin-exchange relaxation-free regime[8]. This work represents an improvement by approximately a factor of 100 over cells coated with conventional alkane material[9], and will likely lead to dramatic improvements in all areas mentioned above. This work was supported by the Office of Naval Research and by the National Science Foundation.

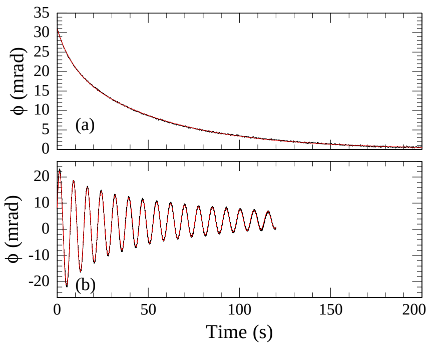


Figure 1: *Decay of longitudinal (a) and transverse (b) polarization. The slow decay time constants for these two data sets are 53 and 77 seconds, respectively.*

[1]H. G. Robinson, and C. E. Johnson, Applied Physics Letters **40**, 771 (1982).
[2]D. Budker, and M. V. Romalis, Nature Physics **3**, 227 (2007).
[3]B. Julsgaard *et al.*, Nature **432**, 482 (2004).
[4]A. Kuzmich, L. Mandel, and N. P. Bigelow, Phys. Rev. Lett. **85**, 1594 (2000).
[5]W.Wasilewski *et al.*, Phys. Rev. Lett. **104**, 133601 (2010).
[6]W.C. Griffith *et al.*, Phys. Rev. Lett. **102** 101601, (2009).
[7]M.V. Balabas, T. Karaulanov, M.P. Ledbetter, D. Budker, arXiv:1005.1617 (2010).
[8]I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, Nature **422**, 596 (2003).
[9]H. G. Robinson, E. S. Ensberg, and H. G. Dehmelt, Bull. Am. Phys. Soc. **3**, 9 (1958).

Long-range interactions of atomic systems

J. Mitroy, J.Y. Zhang

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

The advent of cold atom physics has resulted in long range atomic interactions becoming a topic of increasing importance in atomic structure physics. London dispersion interactions are important in photodissociation dynamics and in the determination of atom-atom scattering lengths from vibrational energy level spacings. There are also dimer states whose existence is largely determined by the long range dispersion forces. Besides the dispersion forces, atomic polarization interactions describe the response of atomic energy levels to ambient electric fields, with the blackbody radiation shift associated with the clock transitions in optical frequency standards.

We are engaged in a project to reduce the determination of atomic dispersion forces to a mechanical procedure. General formulae for systematically evaluating the long-range polarization and dispersion interactions described by LS coupling approximation for atoms have been developed. The dispersion coefficients between any two atoms are evaluated in terms of sum rules involving reduced matrix elements. The accuracy of the dispersion and polarization parameters ultimately depends on the accuracy of the representation of the excited atoms. A computationally inexpensive frozen core model is capable of giving good agreement (1-2%) with more sophisticated many-body calculations provided the core is properly included in all aspects of dispersion calculation.

Sets of reduced matrix elements needed to determine the dispersion coefficients have been produced for the low-lying states of the following atoms H, He, Ne, Ar, Kr, and Xe; Li, Na, K and Rb; Be, Mg, Ca and Sr, F and Cl and finally the group 1B atoms, Cu and Ag. Matrix elements have also been accumulated for some singly charged cations, Be^+, Mg^+, Ca^+, Sr^+ and Al^+. Consequently, it is possible to evaluate the dispersion interaction for many combinations of the low lying states involving these atoms. Besides dispersion interactions, static and dynamic polarizabilities and related quantities can also be produced.

Microwave–Induced Feshbach Resonances

D.J. Papoular[1], G.V. Shlyapnikov[1], J. Dalibard[2]

[1] *Laboratoire de Physique Théorique et Modèles Statistiques, CNRS, U. Paris–Sud, France*
[2]*Laboratoire Kastler Brossel, CNRS, UPMC, Ecole Normale Supérieure, Paris, France*

Cold atomic gases constitute model systems to investigate a wealth of collective quantum phenomena[1]. One can control the strength of the interparticle interactions in these gases using scattering resonances that occur in a collision between two atoms with low energy. These Fano–Feshbach resonances arise when the entrance collision channel is coupled to another channel that supports a weakly–bound molecular state[2]. They are usually obtained using an external static magnetic field. However, for some atomic species, such as Sodium 23 or Rubidium 87, all available static–field resonances are narrow and occur for large magnetic fields, which severely limits their use in experiments. We propose an alternative to static–field FFRs, where the coupling is achieved using a resonant microwave magnetic field[3]. Our scheme is reminiscent of optical Feshbach resonances[4]. It applies to any atomic species with a ground state that is split by hyperfine interaction. We discuss more specifically the case of alkali atoms and calculate the change in the scattering length for $^{7}\mathrm{Li}$, $^{23}\mathrm{Na}$, $^{41}\mathrm{K}$, $^{87}\mathrm{Rb}$, and $^{133}\mathrm{Cs}$. Our results yield optimistic prospects for experiments with the four latter species.

[1]I. Bloch, J. Dalibard, and W. Zwerger, Rev. Mod. Phys. **80**, 885 (2008).
[2]C. Chin, R. Grimm, P. Julienne, and E. Tiesinga, Rev. Mod. Phys. **82**, 1225 (2010).
[3]D. Papoular, G. Shlyapnikov, and J. Dalibard, Phys. Rev. A **81**, 041603(R) (2010).
[4]P. Fedichev *et al.*, Phys. Rev. Lett. **77**, 2913 (1996); M. Theis *et al.*, *ibid.* **93**, 123001 (2004).

Dipole blockade and counting statistics in ultra-cold and Bose condensed Rydberg samples

J. Radogostowicz[1], D. Ciampini[1,2], M. Viteau[2], M.G. Bason[2], N. Malossi[1], O. Morsch[2], E. Arimondo[1,2]

[1]*CNISM, Dipartimento di Fisica E. Fermi, Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy*
[2]*INO-CNR, Dipartimento di Fisica E. Fermi, Università di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy*

In recent years, cold Rydberg atoms have been the subject of intense study because of their large electric dipole moments that lead to long-range dipole-dipole interactions. The dipole blockade effect, in which atoms excited by the same driving pulse may prevent other atoms from being excited, has recently been used for the creation of entangled states and the realization of a quantum logic gate.

Here we extend these results to a larger number of ultra-cold and Bose-condensed Rb atoms in magneto-optical and dipole traps. In the relatively dilute atomic clouds in a magneto-optical trap we characterized the dipole blockade through the counting statistics of the Rydberg atoms created. In the blockaded regime (for $n > 60$) we find negative Mandel-Q parameters, indicating strongly sub-Poissonian counting statistics (Fig. 1a). The negative Q regime is extremely sensitive to the detuning from resonance of the Rydberg excitation, with even a few MHz detuning leading to highly super-Poissonian statistics.

We also investigated Rydberg excitations in an elongated Bose condensate. By changing the length of the elongated cloud between a few microns and several hundreds of microns we observed an increasing number of Rydberg atoms as more and more blockade spheres fit into the (effectively) one-dimensional chain (Fig. 1b).

Financial support by EU Network ”EMALI, by EU-STREP ”NAMEQUAM” and by CNISM ”Progetto Innesco 2007” is gratefully acknowledged.

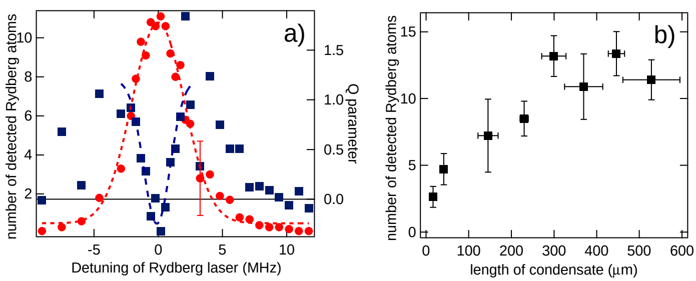


Figure 1: *(a) Rydberg number (circles) and Q-factor (squares) for excitation of the 80s state in a magneto-optical trap. (b) Rydberg number (78d state) as a function of condensate size.*

Progress towards using partial wave scattering for analysing Feshbach resonances

A. Rakonjac[1], D.D. Hudson[1], S. Hoinka[1,2], A.C. Wilson[1,3]

[1] *Jack Dodd Centre for Quantum Technology, Department of Physics, University of Otago, Dunedin, New Zealand*
[2] *ACQAO, Swinburne University of Technology, Hawthorn, Victoria, Australia, 3122*
[3] *National Institute of Standards and Technology, Boulder, CO, USA*

As an external magnetic field B_{ext} approaches a Feshbach resonance, the scattering length of interacting atoms approaches infinity, strongly altering their behaviour. Most methods for characterising Feshbach resonances rely on measuring loss of atoms due to increased collision rates[1,2] or radio frequency spectroscopy of molecules formed by magnetic association[3]. We propose a new method for analysing Feshbach resonances by directly imaging partial wave interference patterns from two ultracold atom clouds in a novel optical collider and extracting the scattering length. The optical collider is a double cross-dipole trap that accelerates two ultracold clouds towards one another and allows full control over the collision energy.

Our experimental apparatus is a ^{40}K-^{87}Rb system. We load ^{87}Rb and ^{40}K into spatially overlapping magneto-optical traps (MOT) and transport them to the ultra-high vacuum end of the vacuum chamber using a mechanical transfer scheme. The atoms are then loaded into a Ioffe-Pritchard trap. At present, we have a double species MOT and have cooled ^{87}Rb to 450 nK using radio frequency evaporation. The ^{40}K atoms will be cooled by sympathetic cooling with ^{87}Rb. Both species will be loaded into an optical dipole trap and ^{87}Rb will be selectively removed. In preparation for colliding, the ^{40}K cloud is split into two by evolving the single cross-dipole trap into two cross-dipole traps using an acousto-optic modulator driven at two frequencies. The collision energy is determined by the relative speed of the clouds upon colliding and is an externally tunable parameter. The resulting scattering pattern is imaged with a resonant light pulse and the scattering length can then be extracted from the absorption image[4]. ^{40}K is chosen for collision experiments because it has more easily experimentally accessible Feshbach resonances than ^{87}Rb, though future experiments may involve both species. In this poster, we report on our experimental progress and give details on our proposed experiment.

---

[1] C. Chin, V. Vuletić, A.J. Kerman, S. Chu, E. Tiesinga, P.J. Leo and C.J. Williams, Phys. Rev. A 70, 032701 (2004)

[2] S. Jochim, M. Bartenstein, G. Hendl, J. Hecker Denschlag, R. Grimm, A. Mosk and W. Weidmüller, Phys. Lett. Rev., 89, 273202 (2002)

[3] C. Chin, A.J. Kerman, V. Vuletić and S. Chu, Phys. Rev. Lett. 90, 033201 (2003)

[4] N. Kjaergaard, A.S. Mellish and A.C. Wilson, N. J. Phys., 6, 146 (2004)

Heading Error of an Alignment-Based Atomic Magnetometer Operating in Earth's Field†

B. Patton[1], O. O. Versolato[2], D. C. Hovde[3], S. Rochester[1], E. Corsini[1], D. Budker[1,4]

[1]*UC Berkeley Physics Department, Berkeley, CA, USA*
[2]*Kernfysisch Versneller Instituut, University of Groningen, The Netherlands*
[3]*Southwest Sciences Inc., Cincinnati, OH, USA*
[4]*Nuclear Science Division, Lawrence Berkeley National Lab, Berkeley, CA, USA*

Atomic magnetometers have surpassed SQUIDs as the world's most sensitive magnetic-field detectors[1]. In low-field environments, atomic magnetometers operating in the SERF (spin-exchange relaxation free) regime are capable of precisions[2] better than 1 fT/Hz$^{1/2}$. At Earth's field, the accuracy of alkali-vapor atomic magnetometers suffers because of systematic shifts in the magnetic resonance frequency which depend upon the magnetometer's orientation in the external field. This effect, termed "heading error", arises from unequal optical pumping of different magnetic transitions which are no longer degenerate at moderate fields because of nonlinear Zeeman shifts.

Although atomic magnetometry is traditionally performed with a circularly polarized pump beam, optical pumping with linearly polarized light is predicted to result in a lower heading error due to the higher-order symmetry (alignment) this generates in the atoms. We have experimentally verified this effect using a portable rubidium-based magnetometer constructed at UC Berkeley. This magnetometer can be operated in driven oscillation mode or in spontaneous self-oscillating mode[3]. Heading error measurements will be presented for both cases and compared to theory.

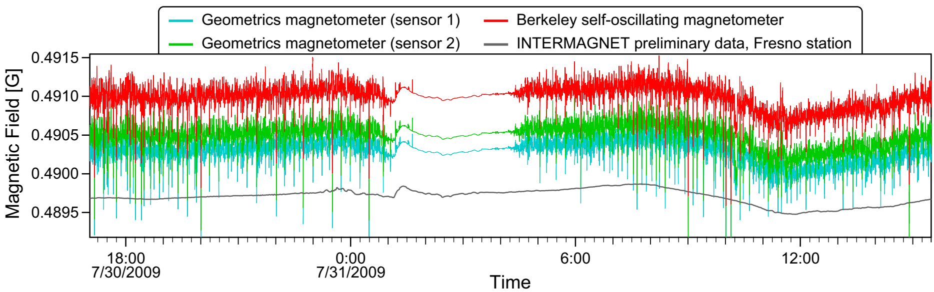


Figure 1: *Concurrent magnetic field data recorded by the UC Berkeley self-oscillating magnetometer (red), a two-channel commercial magnetometer (green and blue), and the INTERMAGNET observatory in Fresno (grey). Note the large magnetic contribution due to the BART (train) system, which discontinues service from ∼1 AM to ∼5 AM.*

†This research was supported in part by the Navy (contract number N68335-06-C-0042), by NASA (contract NNX07CA59P), and by the Department of Energy through grant DE-FG02-08ER84989.

[1]D. Budker and M. V. Romalis, Nature Physics **3**, 227 (2007).

[2]H. B. Dang, A.C. Maloof, and M. V. Romalis, http://arxiv.org/abs/0910.2206v1 (2009).

[3]J. M. Higbie, E. Corsini, and D. Budker, Review of Scientific Instruments **77**, 113106 (2006).

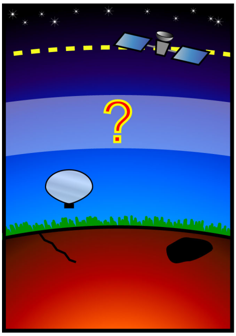
Magnetometry in the Mesospheric Sodium Layer†

J. Higbie[1], B. Patton[2], S. Rochester[2], R. Holzlöhner[3], D. Bonaccini Calia[3], D. Budker[2,4]

[1]*Department of Physics, Bucknell University, Lewisburg, PA, USA*
[2]*UC Berkeley Physics Department, Berkeley, CA, USA*
[3]*European Southern Observatory, Garching, Germany*
[4]*Nuclear Science Division, Lawrence Berkeley National Lab, Berkeley, CA, USA*

As the world's most sensitive magnetic-field measuring devices, atomic magnetometers have found widespread application in a variety of disciplines ranging from fundamental science to nuclear magnetic resonance, geophysics, and medicine[1]. Here we propose to extend the techniques of atomic magnetometry to a more exotic atomic system: sodium atoms in the Earth's mesosphere.

Within the Earth's atmosphere a band of free sodium atoms exists at altitudes of 90–100 km. This mesospheric sodium layer is the basis for "laser guide stars" employed in observational astronomy[2,3]. We outline an experiment to use the ^{23}Na atoms in this layer for high-precision atomic magnetometry[4]. Such a measurement would yield geomagnetic data on a previously unexplored length scale. A description of the proposed experiment (Fig. 1) will be presented, as well as some interesting challenges inherent in performing an atomic physics experiment outside the confines of the laboratory.



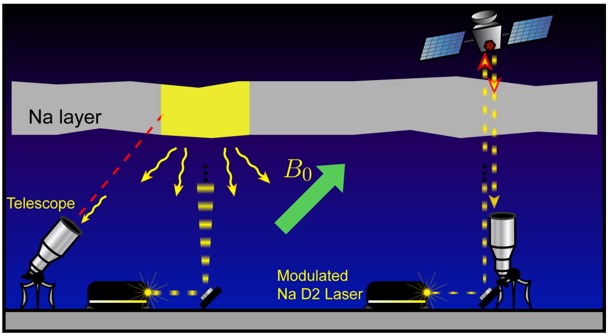


Figure 1: ***Left***: *Although extensive geomagnetic field measurements have been made at low altitudes and along satellite orbits, the Earth's magnetic field has not been mapped at intermediate distances* (e.g., *the altitude of the mesospheric sodium layer). Such measurements could be valuable in detecting oil/mineral deposits, earthquake-prone faults, or mesoscopic ocean current variability.* ***Right***: *Two proposed measurement schemes.*

†This research has been supported by the NURI program.

[1]D. Budker and M. V. Romalis, Nature Physics **3**, 227 (2007).
[2]W. Happer *et al.*, J. Opt Soc. Am. A **11**, 263 (1994)
[3]R. Holzlöhner *et al.*, Astronomy & Astrophysics **510**, 14 (2010).
[4]J. Higbie *et al.*, http://arxiv.org/abs/0912.4310

Interference in intrashell crossings caused by two hidden crossings

I. Pilskog[1,2], D. Fregenal[3], M. Førre[1], E. Horsdal[4], A. Waheed[1]

[1]*Department of physics and technology, University of Bergen, Bergen, Norway*
[2]*Laboratoire de Chemie Physique Matière et Rayonnement, Univerité Pierre et Marie Curie, Paris, France*
[3]*Centro Atomico Bariloche, Rio Negro, Argentina*
[4]*Department of Physics and Astronomy, Aarhus University, Denmark*

Regular oscillations (see Fig. 1) in the adiabatic transition probability as a function of the angle between the initial electric field (145V/cm)) and the final field (6.27V/cm), superimposed on a constant uniform magnetic field (25G) has been observed in experiments with circular lithium Rydberg atoms (n=25)[1]. Theoretical calculations show that the fields control the Stark-Zeeman splitting of the shell and reveal two closely spaced hidden crossings. Introduction of a rotating electric field ($\Omega/2\pi = 30$MHz and stengths up to 0.1180V/cm) enables transitions for a wider range of angles.

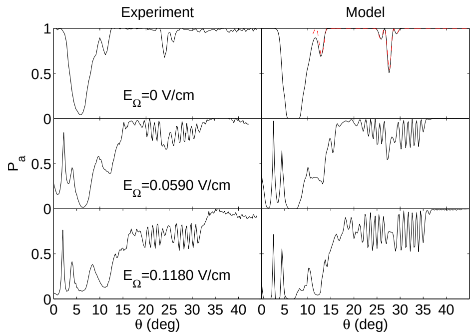


Figure 1: *The adiabatic transition probability as a function of the angle between the initial electric field and the final field. To the left are experimental observed probabilities and to the right are theoretical results.*

[1]M. Førre *et al.*, J.Phys B **35**, 401-419 (2002)

Broadband adiabatic conversion of light polarization

A. A. Rangelov[1], U. Gaubatz[2], N. V. Vitanov[1]

[1]*Department of Physics, Sofia University, James Bourchier 5 blvd, 1164 Sofia, Bulgaria*
[2]*Nokia Siemens Networks GmbH And Co. KG, St.-Martin-Strasse 76, 81541 Munich, Germany*

A broadband technique for robust adiabatic rotation and conversion of light polarization is proposed[1]. It uses the analogy between the equation describing the polarization state of light propagating through an optically anisotropic medium and the Schrödinger equation describing coherent laser excitation of a three-state atom [2]. The proposed technique is analogous to the stimulated Raman adiabatic passage (STIRAP) technique in quantum optics [3]; it is applicable to a wide range of frequencies and it is robust to variations in the propagation length and the rotary power.

[1]A. A. Rangelov, U. Gaubatz, N. V. Vitanov, http://arxiv.org/abs/0910.0162
[2]A. A. Rangelov, N. V. Vitanov, and B. W. Shore, J. Phys. B **42**, 055504 (2009)
[3]U. Gaubatz, P. Rudecki, S. Schiemann, and K. Bergmann, J. Chem. Phys. **92**, 5363 (1990)

Autler-Townes doublet and electromagnetically-induced transparency resonance probed by an ultrashort pulse train

A. A. Soares[1], L. E. E. de Araujo[2]

[1]*Universidade Federal de São Carlos, Campus Sorocaba, Sorocaba - SP, 18052-780, Brazil*

[2]*Instituto de Física "Gleb Wataghin," Universidade Estadual de Campinas, Campinas - SP, 13083-970, Brazil*

High resolution spectroscopy and optical metrology have seen large advances due to development of phase stabilized femtosecond lasers[1]. Although ultrashort laser pulses have large spectral bandwidths, the spectrum of a train of such pulses shows a comb-like structure of frequency peaks, each one with a linewidth inversely proportional to the number of pulses in the train. For a large number of pulses the peaks can be extremely narrow, enabling high resolution spectroscopy. Frequency comb devices based on ultrashort lasers pulses have been used in high resolution spectroscopy of one and two photon transitions[2,3]. Direct frequency comb spectroscopy has been developed[4], allowing simultaneous high-resolution spectroscopy and time-resolved investigation of atomic dynamics; kHz resolution spectroscopy of cold Ca atoms has been demonstrated[5].

In this work we investigate the interaction between an ultrashort pulse train with a three-level atom in the lambda configuration. The atomic system is driven resonantly by a cw coupling laser and the excited-state lifetime is T_1 = 28 ns. The pulses are classical and with a repetition period T = 10 ns. Because the train repetition period is shorter than the excited-state lifetime, the atom does not have enough time to completely decay in between pulses and excitation accumulates from one pulse to the next[3,4]. We show that, depending on the coupling Rabi frequency, the pulse train can be used to observe spectra of Autler-Townes (AT) doublet or an electromagnetically induced transparency (EIT) resonance. In the AT case, the pulse train can selectively excite one component of the AT doublet. Another feature is that the AT doublet can be coherently excited if the Rabi frequency matches to a harmonic of the pulse repetition rate and in such a situation the temporal evolution of the excited atomic population shows quantum beats between the two AT components. In the stationary regime the EIT resonance shows a subnatural linewidth and the absorption goes to zero excitation at zero probe detuning.

---

[1]Th. Udem, R. Holzwarth and T. W. Hänsch, Nature **416**, 233 (2002).
[2]V. Gerginov, C. E. Tanner, S. A. Diddams, et al., Opt. Lett. **30**, 1734 (2005).
[3]M. C. Stowe, F. C. Cruz, A. Marian, et al., Phys. Rev. Lett. **96**, 153001 (2006).
[4]A. Marian, M. C. Stowe, J. R. Lawall, et al., Science **306**, 2063 (2004).
[5]T. M. Fortier, Y. Le Coq, J. E. Stalnaker, et al., Phys. Rev. Lett. **97**, 163905 (2006).

The equilibrium state of a trapped two-dimensional Bose gas

K. J. Günter[1], S. P. Rath[1,2], T. Yefsah[1], M. Cheneau[1,3], R. Desbuquois[1], M. Holzmann[4], W. Krauth[5], J. Dalibard[1]

[1] *Laboratoire Kastler Brossel, CNRS, UPMC, Ecole Normale Supérieure, Paris, France*
[2] *Physik Departement, TU München, Germany*
[3] *MPI für Quantenoptik, Garching, Germany*
[4] *LPMC, CNRS, UPMC, Paris and LPMMC, CNRS-UJF, Grenoble, France*
[5] *Laboratoire de Physique Statistique, CNRS, Ecole Normale Supérieure, Paris, France*

Low-dimensional quantum systems exhibit enhanced thermal and quantum fluctuations, and 'beyond mean-field' effects are more apparent than in three dimensions. An interesting feature specific to the uniform two-dimensional (2D) Bose gas is the approximate scale invariance of its equation of state. We have measured equilibrium density profiles of a single trapped 2D Bose gas, which can be related to the equation of state of the homogeneous system using the local density approximation[1].

For trapped clouds we find that multiple scattering of probe photons at high atomic densities lead to a detection deficiency in absorption imaging. We circumvent this problem by letting the cloud expand in the 2D plane to reduce its density. During such an expansion a dynamical self-similarity of the density profile provides us with a powerful zoom function for the initial distribution. Our measurements are in very good agreement with the results of quantum Monte-Carlo simulations.

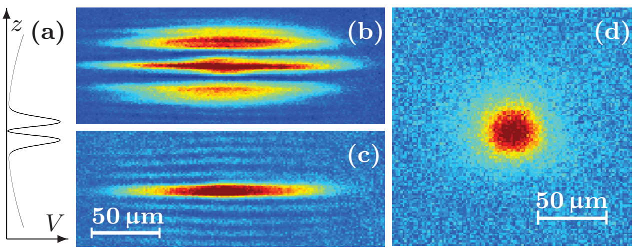


Figure 1: *Preparation of a single 2D Bose gas of ^{87}Rb atoms. (a) Potential V along the vertical z direction produced by a magnetic TOP trap and a blue-detuned laser beam; (b) side view of atoms loaded into this potential; (c) side view of a 2D cloud after depumping the atoms in the lateral wells; (d) top view of the 2D cloud.*

[1] S. P. Rath *et al.*, arXiv:1003.4545, submitted (2010).

Number Phase Wigner Representation for Efficient Stochastic Simulation

M.R. Hush[2], A.R.R. Carvalho[1,2], J.J. Hope[1,2]

[1]*ACQAO, College of Science, The Australian National University*
[2]*Department of Quantum Science, Research School of Physics and Engineering*

Multimode simulation for extended periods of a Bose Einstein Condensate (BEC) is still an incomplete problem in atom optics. Achieving this goal is important for both understanding experiments where mean field and perturbative methods fail and also in the search for new and exciting physics. Multimode simulations allow exotic quantum states to be investigated which are impossible with semi-classical approaches.

Traditionally multimode simulations have been performed using phase space representations based on coherent states examples include the Wigner representation, positive P and Q[1]. By combining the equation of motion produced by these representations with a Fokker-Plank equation, one can produce a set of stochastic differential equations (SDEs) which can greatly reduce the dimensionality of a problem. For example consider a BEC modelled as a set of N harmonic oscillators. This would typically require a density matrix with D^{2N} components to solve directly (where D is the number of elements you have in your truncated basis). Using a phase space representation one can change this to a set of only N SDEs. This makes previously unfeasibly large (in memory) simulations now possible on even desktop computers. These results also have applications beyond BEC and can be applied to many different large quantum systems.

Unfortunately the nonlinear term in the BEC's equation of motion can severely limit integration times. We hypothesise this is because the coherent basis is inappropriate for this term and that a number-phase based alternative will do better. Historically the investigations of number-phase space methods have been primarily concerned with the visualisation of quantum states and no simple extension can be used to generate SDEs. We present a novel number-phase Wigner representation that does generate SDEs. We investigate the properties of this new distribution and use it to simulate a Bose-Hubbard model with two locations. We show the new number Wigner based representation converges for longer than any other scalable integration method, by comparing it to a direct integration of the master equation.

These results show this representation has great potential, particularly in the field of BEC simulation. It also has the possibility to be used in other areas. We intend to continue investigating this new representation and hopefully apply it to larger multimode problems to help better understand experiments and also explore new physics.

[1]C.W. Gardiner, Handbook of stochastic Methods, Springer-Verlag (1983).

Geometric operations of a Sodium Bose-Einstein condensate in an optical lattice

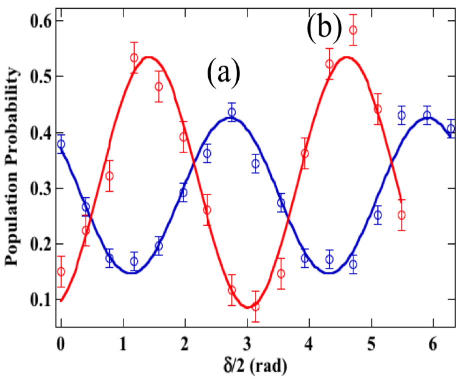
Hiromitsu Imai, Tomoya Akatsuka, Takashi Ode, and Atsuo Morinaga

Tokyo University of Science, Noda-shi, Chiba, Japan

Nowadays, optical lattice is used for various researches such as optical frequency standards for next generation ”clock”, a robust quantum memory for quantum computations and atom interferometers for precise measurements. We are aiming to accomplish a robust geometric universal single qubit operation, using Bose-Einstein condensates (BECs) in an optical lattice.

With released BECs of sodium atoms, the Bloch vecter of the two level BECs were rotated around axes 3 and 2 on the Bloch sphere by geometric operations with two $\pi/2$ resonant pulses whose second pulse has a relative phase of $\delta/2$ (Fig. 1a) and three successive $\pi/2$-π-$\pi/2$ pulses whose central pulse has arelative phase of $\delta+\pi/2$ (Fig. 1b)[1]. However, with BECs released atoms from the magnetic trap the operation time was limited due to the gravity. Therefore, we trapped BECs in a one-dimensional optical lattice with a potential depth of 30 μK which was generated from a retro-reflected YAG laser. Figure 2 shows an absorption image of BECs in an optical lattice and the lifetime was about 500ms. We measured frequencies of vibrational levels of F=1 states with two-photon stimulated Raman spectroscopy and coherence time between F=1 and F=2 using Rabi oscillation and atom interferometer which was composed of two $\pi/2$ pulses with a time interval of T.

In the poster sessions, we report results of Ramsey atom interferometer of sodium atoms trapped in optical lattice and geometric operation using resonant laser-controlled Raman pulses.



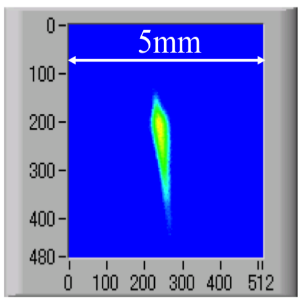


Figure 1: *Geometric rotations around axes 3 (a) and 2 (b) of released BECs*

Figure 2: *Absorption image of BECs in optical lattice at 200 ms after trapping*

[1] H. Imai and A. Morinaga, Phys. Rev. A 78, 010302 (R)(2004).

The fountain effect in a Bose-Einstein condensate

T. Karpiuk[1], B. Grémaud[1,2,3], C. Miniatura[1,2,4], B.-G. Englert[1,2], M. Gajda[5,6]

[1]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore*
[2]*Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117542, Singapore*
[3]*Laboratoire Kastler Brossel, Ecole Normale Supérieure, CNRS, UPMC; 4 Place Jussieu, 75005 Paris, France*
[4]*Institut Non Linéaire de Nice, UMR 6618, UNS, CNRS; 1361 route des Lucioles, 06560 Valbonne, France*
[5]*Instytut Fizyki, Polska Akademia Nauk, Warsaw, Poland*
[6]*WMP-SNŚ, UKSW, Warsaw, Poland*

The fountain effect called also the thermomechanical effect is one of the most spectacular results of superfluid properties of ^{4}He discovered in 1938 by Kapitza[1], and independently by Allen and Misener[2]. We theoretically investigate a possibility of an experimental implementation of the fountain effect in a Bose-Einstein condensate of alkali atoms. We use the classical field approximation of the version described in [3] and optimized for an arbitrary trapping potential in [4].

[1]P.L. Kapitza, Nature (London) **141**, 74 (1938).
[2]J.F. Allen and A.D. Misener, Nature (London) **141**, 75 (1938).
[3]M. Brewczyk, M. Gajda, and K. Rzążewski, J. Phys. B **40**, R1 (2007).
[4]T. Karpiuk, M. Brewczyk, M. Gajda, and K. Rzążewski, Phys. Rev. A **81**, 013629 (2010).

On the momentum distribution of a harmonically trapped 1D Bose gas

K.V. Kheruntsyan[1], M.J. Davis[1], P.B. Blakie[2], A.H. van Amerongen[3], N.J van Druten[3]

[1]*ARC Centre of Excellence for Quantum-Atom Optics, School of Mathematics and Physics, University of Queensland, Brisbane, Queensland 4072, Australia*
[2]*Jack Dodd Centre for Quantum Technology, Department of Physics, University of Otago, Dunedin, New Zealand*
[3]*Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands*

Experimental measurements of the momentum distribution of a harmonically trapped 1D Bose gas were recently reported by Van Amerongen *et al.*[1]. Quantitative understanding of the measured distributions currently pose a theoretical challenge as the experiments included the so called decoherent quantum regime of the 1D Bose gas, which is not amenable to simple theoretical treatment. The decoherent quantum regime is characterised by the presence of both density and phase fluctuations and stands in between the classical ideal gas regime and a quasi-condensate regime in which the density fluctuations are suppressed while the phase still fluctuates.

Even though the 1D Bose gas model with repulsive δ-function interactions is exactly solvable in the uniform limit[2], the construction of the momentum distribution using the known Bethe ansatz solutions is a challenging problem yet to be solved. Finite temperature properties of the 1D Bose gas in the thermodynamic limit can be studied using the Yang-Yang thermodynamics formalism[3], however, this again does not yield the momentum distribution of the 1D Bose gas. What can be done, however, using the Yang-Yang formalism is to calculate the kinetic energy per particle of the system at arbitrary interaction strengths and arbitrary temperatures. This in turn gives the rms width of the momentum distribution of the gas, which is an important quantity that can be compared with the rms width of an experimentally measured momentum distribution using the local density approximation. It can also be used to benchmark approximate numerical approaches in different regimes of the 1D Bose gas problem.

We have calculated the rms width of the momentum distribution of a harmonically trapped 1D Bose gas using the Yang-Yang thermodynamics solutions and the local density approximation. We are currently in the process of comparing these results with the experimentally measured widths, as well as with the numerically computed momentum distributions using the stochastic Gross-Pitaevskii approach.

[1]A. H. van Amerongen, J. J. P. van Es, P. Wicke, K. V. Kheruntsyan, and N. J. van Druten, Phys. Rev. Lett. **100**, 090402 (2008).

[2]E. H. Lieb and W. Liniger, Phys. Rev. **130**, 1605 (1963).

[3]C. N. Yang and C. P. Yang, J. Math. Phys. **10**, 1115 (1969).

A parametric amplifier of matter waves

C. Klempt[1], M. Scherer[1], B. Lücke[1], O. Topic[1], G. Gebreyesus[3], F. Deuretzbacher[3], L. Santos[3], W. Ertmer[1], J. Arlt[2]

[1]*Institut für Quantenoptik, Leibniz Universität Hannover, D-30167 Hannover, Germany*
[2]*QUANTOP, Department of Physics and Astronomy, University of Aarhus, 8000 Århus C, Denmark*
[3]*Institut für Theoretische Physik, Leibniz Universität Hannover, D-30167 Hannover, Germany*

Matter wave optics with ultracold samples has reached the point where non-classical states can be prepared and their fascinating properties can be explored. In optics, parametric down conversion is routinely used to generate light with squeezed observables as well as highly entangled photon pairs. The applications of these non-classical states range from fundamental tests of quantum mechanics to improved interferometers and quantum computation. Therefore, it is of great interest to realize such non-classical states with matter waves. Bose-Einstein condensates with non-zero spin can provide a mechanism analogous to parametric down conversion, thus enabling the generation of non-classical matter waves. We observed magnetic field dependent spin resonances [1] where the spin dynamics is enhanced and acts as an exponential amplifier. We demonstrate that this parametric amplification can amplify both classical matter waves as well as vacuum fluctuations to macroscopic clouds [2]. Depending on the magnetic field, the clouds are created in excited spatial modes (see Fig. 1). We find that these spatial modes can break both spatial and spin symmetries spontaneously. In the future, these non-classical matter waves can be used as a source for Bell pairs of neutral atoms as well as an input for Heisenberg limited atom interferometers.

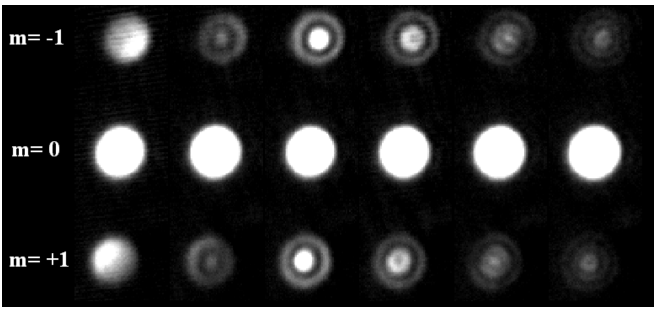


Figure 1: *Parametric amplification of excited spatial modes. Absorption images of spinor condensates after the separation of the spin components m for increasing magnetic field (from left to right).*

[1] C. Klempt, O. Topic, G. Gebreyesus, M. Scherer, T. Henninger, P. Hyllus, W. Ertmer, L. Santos, and J. Arlt, Phys. Rev. Lett. **103**, 195302 (2009).

[2] C. Klempt, O. Topic, G. Gebreyesus, M. Scherer, T. Henninger, P. Hyllus, W. Ertmer, L. Santos, and J. Arlt, **104**, 195303 (2010).

Classification of topological excitations with influence of vortices

S. Kobayashi[1], M. Kobayashi[2], Y. Kawaguchi[1], M. Nitta[3], and M. Ueda[1]

[1]*Department of Physics, University of Tokyo, Tokyo, Japan*
[2]*Department of Basic Science, University of Tokyo, Tokyo, Japan*
[3]*Department of Physics, Keio University, Tokyo, Japan*

Classification of topological excitaions is helpfull to understand what kind of topological excitations exist in ordered systems. In many cases, topological excitaions are classified by homotopy theory, i.e., topological excitaions are distinguished by mapping of n-dimensional sphere in real space to order parameter space[1].

However, monopoles in a nematic liquid crystal cannot be classified by the conventional homotopy theory in the presence of vortices[1], because the topological invariants defined by the conventional homotopy theory to the influence of a vortex. In this work, we propose the new invariants to describe the influence of two types of topological excitations by using Abe homotopy[2] and Fox homotopy[3], in which we consider a mapping of n-dimensional pinched tourus.

We show a few applications of these homotopy groups in some ordered systems and explain the systmatic method to calculate the influence on topological excitations.

[1]N. D. Mermin, Rev. Mod. Phys. **51** 591 (1979)
[2]M. Abe, Jap. J. Math **16** 179 (1940)
[3]R. H. Fox, Ann. of Math. **49** 471 (1947)

A Bose-Einstein Condensate of Calcium

S. Kraft, F. Vogt, O. Appel, S. Schulz, M. Kahmann, U. Sterr, F. Riehle

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

Ultracold quantum gases of alkaline earth atoms attract attention due to their possible applications in optical clocks, in quantum computing, and in quantum metrology. Recently, we have achieved Bose-Einstein condensation of ^{40}Ca[1]. Due to the large ground state s-wave scattering length and associated large three body losses an optimized loading and cooling scheme was necessary to condense about $2 \cdot 10^4$ atoms. Our cooling scheme consisting of a two-stage magneto-optical trap and subsequent forced evaporation in a crossed dipole trap at magic wavelength allows to reach degeneracy within less than 3 s. Here we present the optimized route to BEC and discuss future applications.

[1] S. Kraft, F. Vogt, O. Appel, F. Riehle, and U. Sterr, Phys. Rev. Lett. **103**, 130401 (2009).

Landau-level Mixing Effect on Rotating Bose-Einstein Condensate with Attractive Interaction in Anharmonic Trapping Potential

Shang-Tun Lin[1], Szu-Cheng Cheng[2], Wen-Hsuan Kuan[1]

[1] *Department of Science, Taipei Municipal University of Education, Taipei 10048, Taiwan.*
[2] *Department of Physics, Chinese Culture University Yang Ming Shan, Taipei 111, Taiwan.*

We apply the Gross-Pitaevskii equation to explore the dynamics of rotating Bose-Einstein condensate with attractive interaction in anharmonic trapping potential. Consider Landau-level mixing (LLM) effect, variational wave functions are proposed to describe the ground-state properties of vortex and center-of-mass states. Without LLM both states have exactly same energies obtained by the perturbation theory, whereas vortex state energy is lowered if LLM is considered. We show that LLM stabilize vortex and center-of-mass states effectively which is not negligible even under conditions of weak interaction and weak anharmonic trapping potential.

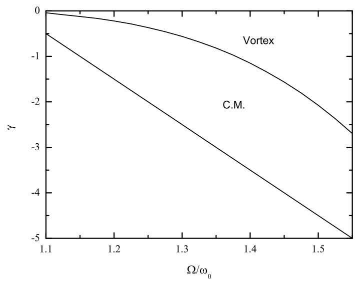


Figure 1: *The phase diagram of the Rotating condensate. LLM is considered in vortex state region whereas center-of-mass state exist in LLL.*

Splitting dynamics of giant vortices in dilute Bose–Einstein condensates

P. Kuopanportti[1], E. Lundh[2], J.A.M. Huhtamäki[1,3], V. Pietilä[1], M. Möttönen[1,4]

[1]*Department of Applied Physics/COMP, Aalto University, P.O. Box 15100, FI-00076 AALTO, Finland*
[2]*Department of Physics, Umeå University, SE-90187 Umeå, Sweden*
[3]*Department of Physics, Okayama University, Okayama 700-8530, Japan*
[4]*Low Temperature Laboratory, Aalto University, P.O. Box 13500, FI-00076 AALTO, Finland*

The experimental realization of quantized vortices in dilute Bose–Einstein condensates in 1999 was an important demonstration of the superfluid properties of these systems. Recently, it has been suggested that giant vortices with very large quantum numbers could be created with the so-called topological *vortex pump*, i.e., by cyclically pumping vorticity into the condensate[1]. In principle, vortices with an arbitrarily large quantum number κ can be produced. In practice, however, κ is limited by the inherent instability of such vortices. Motivated by these aspects, we have theoretically studied the core sizes, dynamical instabilities, and splitting mechanisms of giant vortices in the zero-temperature limit[2].

The giant vortices were found to be dynamically unstable against splitting into singly quantized vortices at nearly all values of the atom–atom interaction strength. When the splitting occurs, it results in the formation of vortex-free condensate fragments separated by vortex sheets. However, as a function of κ, the strength of the dynamical instability increases extremely slowly for large values of κ. The core size of the vortex was found to increase roughly as a square-root function of κ, which makes it possible to gradually increase the operation frequency of the vortex pump without challenging adiabaticity. We also found that vortices with large κ can be rendered dynamically stable with Gaussian potential profiles that are routinely achievable with commercial lasers. Thus, our studies suggest that multiquantum vortices of very high angular momenta may be achieved with the pump.

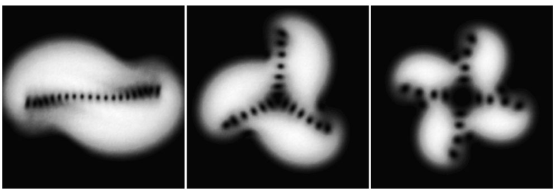


Figure 1: *Splitting patterns of a 20-quantum vortex with different symmetries.*

[1]M. Möttönen, V. Pietilä, and S.M.M. Virtanen, Phys. Rev. Lett. **99**, 250406 (2007).

[2]P. Kuopanportti, E. Lundh, J.A.M. Huhtamäki, V. Pietilä, and M. Möttönen, Phys. Rev. A **81**, 023603 (2010); P. Kuopanportti and M. Möttönen, *ibid.* **81**, 033627 (2010).

Temporal coherence of a Raman-outcoupled continuously pumped atom laser

G.M. Lee[1], S.A. Haine[1], A.S. Bradley[2], M.J. Davis[1]

[1]*The University of Queensland, School of Mathematics and Physics, ARC Centre of Excellence for Quantum-Atom Optics, QLD 4072, Australia.*
[2]*Jack Dodd Centre for Quantum Technology, Department of Physics, University of Otago, PO Box 56, Dunedin, New Zealand*

Continuous-wave atom lasers, which may allow for larger fluxes and longer experimental integration times, have the potential to be used in metrology, interferometry and precision measurements, where the coherence behaviour of the atom laser is intrinsic to its possible success. Thermal fluctuations inherent in all experiments may cause decoherence, reducing the fidelity of possible metrology applications. We present a study of the coherence properties of a continuously-pumped atom laser operating at finite temperature, using the stochastic Gross-Pitaevskii formalism [1] to simulate a continuously-replenished condensate reservoir, from which an atom laser beam is outcoupled with a fixed momentum using a Raman scheme. We find the coherence of the beam matches that of the reservoir for large momentum transfers, but has a shorter coherence time than that of the reservoir at low momentum transfer. A classical model suggests that this is due to thermal fluctuations in the condensate reservoir, leading to a broadening of the momentum distribution of the outcoupled beam. This could be important information for designing a coherent matter wave source for metrology applications.

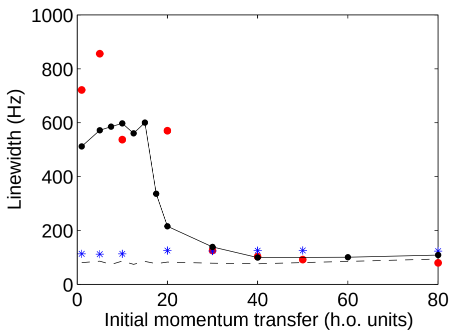


Figure 1: *Comparison of linewidth as a function of initial momentum transfer for both the atom laser simulation (beam: red points, condensate reservoir: blue points) and for a classical model of atoms rolling down a fluctuating potential (kinetic energy spread: solid black line, initial potential energy spread: dashed black line).*

[1]P. B. Blakie, A. S. Bradley, M. J. Davis, R. J. Ballagh and C. W. Gardiner, 'Dynamics and statistical mechanics of ultra-cold Bose gases using c-field techniques', Advances in Physics **57** 363 (2008).

Excitation Frequencies and Static Solutions of Trapped Dipolar BECs in the Thomas Fermi Regime

A.M. Martin[1], R.M.W. van Bijnen[2,3], N.G. Parker[4], S.J.J.M.F. Kokkelmans[2], D.H.J. O'Dell[3]

[1] *School of Physics, University of Melbourne, Parkville, Victoria 3010, Australia*
[2] *Eindhoven University of Technology, PO Box 513, Eindhoven, The Netherlands*
[3] *Department of Physics and Astronomy, McMaster University, Hamilton, Canada*
[4] *School of Food Science and Nutrition, University of Leeds, LS2 9JT, United Kingdom*

We analyse the excitation frequencies[1] [Fig. 1(a)] and static solutions of trapped BECs with dipolar interactions, in the Thomas-Fermi limit. We present a general and versatile method for deriving the static solutions and their excitation frequencies, incorporating analytic expressions for the dipolar potential of an arbitrary polynomial density profile inside the BEC. We show that the collapse of the condensate[2] is mediated by a quadrupolar mode[3]. Motivated by the intriguing possibility of fragmentation in a dipolar BEC which is cigar-shaped[2], and the consequent implications for superfluidity in these systems, we pay particular attention to the scissors modes [Fig. 1(b,c)].

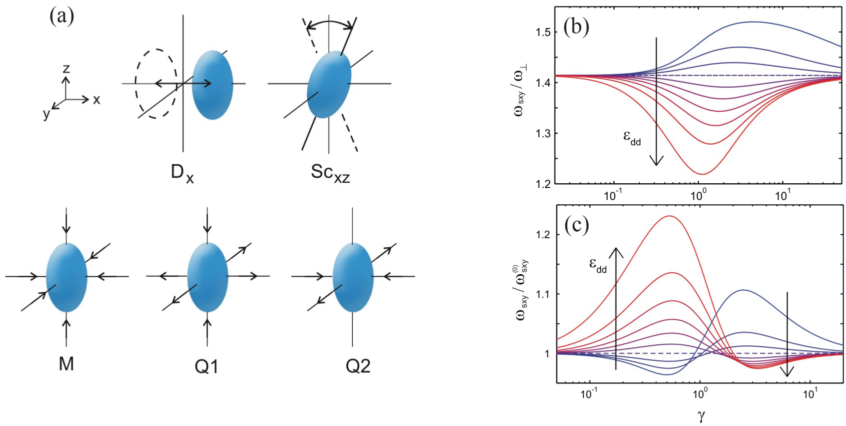


Figure 1: *(a) Illustration of the modes considered: dipole mode, in the x-direction D_x; scissors mode, in x-z plane Sc_{xz}; monopole mode M and quadrupole modes Q_1 and Q_2. (b,c) Scissors frequencies as a functions of the axial trapping strength γ for various strengths of the dipolar interactions, $-0.45 \leq \varepsilon_{dd} \leq 0.9$ (increasing in the direction of the arrow in steps of 0.15). The dashed line indicates $\varepsilon_{dd} = 0$. (b) Frequency of Sc_{xy} mode for fixed trap ellipticity of $\epsilon = 0.1$. (c) Frequency ω_{sxz} of the Sc_{xz} mode for a cylindrically symmetric trap, scaled to the non-dipolar frequency $\omega^{(0)}_{sxz}$.*

[1] G. Bismut *et al.*, arXiv:1005.2493v1.
[2] T. Lahaye *et al.*, Nature **448**, 672 (2007); T. Lahaye *et al.*, Phys. Rev. Lett. **101**, 080401 (2008).
[3] K. Góral and L. Santos, Phys. Rev. A **66**, 023613 (2002).

Spatial Coherent Transport of Interacting Dilute Bose Gases

A.M. Martin[1], M. Rab[1] J.H. Cole[1,2] N.G. Parker[1,3], A.D. Greentree[1], L.C.L. Hollenberg[1]

[1] *School of Physics, University of Melbourne, Parkville, Victoria 3010, Australia*
[2] *Institut für Theoretische Festkörperphysik und DFG-Center for Functional Nanostructures (CFN), Universität Karlsrhue, 76128 Karlsrhue, Germany.*
[3] *School of Food Science and Nutrition, University of Leeds, LS2 9JT, United Kingdom*

We investigate coherent atomic tunneling of a BEC in a three-well system[1], generalizing stimulated Raman adiabatic passage to adiabatically transport a BEC of 2000 ^{7}Li atoms between two wells with minimal occupation in the intervening well. The system considered is schematically shown in Fig. 1(a), where a three-dimensional harmonic trap is split into three regions. With the BEC initially in well 1, we show how, through adiabatic changes to the tunneling rates between the wells, to transport it into well 3 with minimal occupation of the intervening well [Fig. 1(b)]. We elucidate the properties of the three-well system by considering a three-mode approximation, the properties of the equivalent Bose-Hubbard Hamiltonian and numerical simulations of the mean-field Gross-Pitaevskii equation.

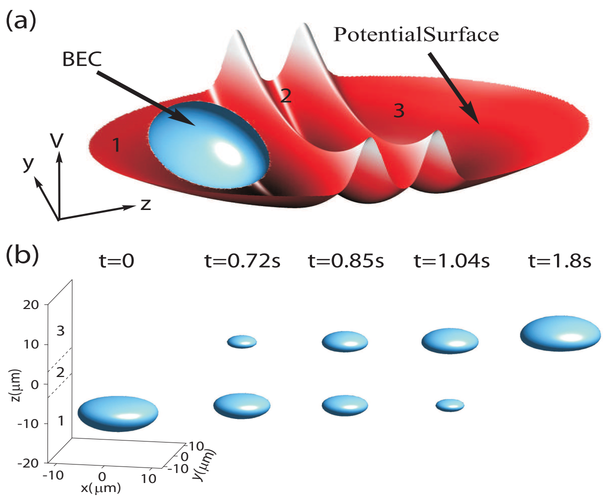


Figure 1: *(a) Schematic representation of the system at $t = 0$ in the $z - y$ plane, with the BEC occupying well* 1. *(b) Isosurface plots of atomic density, $n_{iso} = 0.1n_0$ (n_0 is the initial peak density of the BEC), showing the adiabatic transportation of a BEC of 2000 ^{7}Li atoms over a distance of 20 μm simulated using the three-dimensional 3D Gross-Pitaevskii equation.*

[1] M. Rab *et al.*, Phys. Rev. A **77**, 061602 (2008).

Phase fluctuations in anisotropic Bose condensates: from cigars to rings

L. Mathey, A. Ramanathan, K. C. Wright, S. R. Muniz, W. D. Phillips, and Charles W. Clark

Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, Gaithersburg, Maryland 20899, USA

We study the phase-fluctuating regime of ultra-cold atoms trapped in a ring-shaped trap geometry, which has been realized in Phys. Rev. Lett. **102**, 170401 (2009) and Phys. Rev. Lett. **99**, 260401 (2007). We first consider a simplified box geometry, in which we identify the conditions to create a state that is dominated by thermal phase-fluctuations, and then explore the actual experimental geometry. In both cases we demonstrate that the requirement for strong fluctuations can be expressed in terms of the total number of atoms and the geometric length scales of the trap only. We also address possible ways of detecting this regime.

Dynamics of repulsively and attractively interacting bosons in 1D after an interaction quench

Dominik Muth[1], Bernd Schmidt[1,2] and Michael Fleischhauer[1]

[1] *Fachbereich Physik und Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*
[2] *Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-60438 Frankfurt am Main, Germany*

We theoretically analyze the dynamics of a one dimensional Bose gas with strong short range interactions. In the attractive regime numerical simulations of the many body system reproduce the formation of the metastable super Tonks-Girardeau gas recently observed in cold atom experiments[1]. A quench from the Tonks to the super-Tonks regime leads to a very small coherent admixture of tightly bound-pair states, leading to an oscillatory behavior of the two-particle correlation function. In the repulsive regime we investigate a setup where the numerical simulations show, despite the integrability of the model, local thermalization on a short timescale[2]. The resulting final state is consistent with the results from thermodynamical Bethe ansatz.

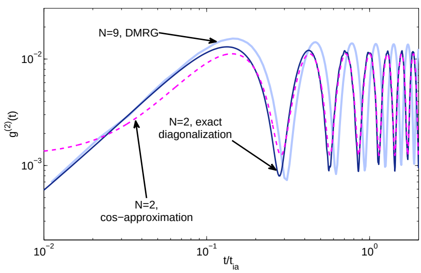


Figure 1: *After a quench from the Tonks gas to strong attractive interactions the two particle correlations remain small. The oscillating behavior reveals a small coherent admixture of bound-pair states. It coincides with the value from a two particle calculation (exact[3] and in two-state quantum beating approximation).*

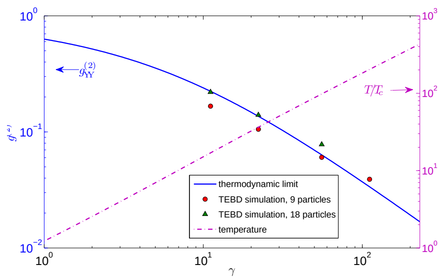


Figure 2: *After a sudden switching on of repulsive interactions, despite integrability local correlation quickly reach a stationary value (symbols), that is well described by the finite temperature ensemble found from thermodynamical Bethe ansatz (continuous line).*

[1] E. Haller, M. Gustavsson, M. J. Mark, J. G. Danzl, R. Hart, G. Pupillo and H. C. Naegerl, *Realization of an Excited, Strongly Correlated Quantum Gas Phase*, Science 325, 1224 (2009)

[2] D. Muth, B. Schmidt and M. Fleischhauer, *Local and non-local relaxation of a 1D Bose gas with finite interactions*, arXiv:0910.1749, 2009

[3] D. Muth, M. Fleischhauer and B. Schmidt, *Discretized vs. continuous models of p-wave interacting fermions in 1D* arXiv:1004.4099, 2010

Dynamical and Landau instabilities of condensed cold atom system in nonequilibrium Thermo Field Dynamics

Y. Nakamura and Y. Yamanaka

Department of Electronic and Photonic Systems, Waseda University, Tokyo, Japan

The nonequilibrium dynamics for the system of cold atoms with a Bose-Einstein condensate is investigated in a framework of nonequilibrium Thermo Field Dynamics (TFD).[1] We consider the system with a time-dependent order parameter and derived the self-consistent equations which describe the temporal evolution of the system, i.e., the time-dependent Gross-Pitaevskii equation, the time-dependent Bogoliubov-de Gennes (TDBdG) equations, and the quantum transport equation.The equations can be applied not only to the usual stable system approaching to equilibrium, but also the unstable one owing to either the Landau instability or the dynamical one, accompanied by the condensate decay.

There are two nonequilibrium extensions of the thermal field theory, i.e., the closed time path and TFD. We employ the TFD formalism here, because the concept of quasiparticle picture is clear even in nonequilibrium situations. In TFD, which is a real-time canonical formalism of the quantum field theory, thermal fluctuation is introduced through doubling the degrees of the freedom, and the mixed state expectation value is replaced by an average by using a pure state pure state vacuum, called the thermal vacuum.

So far we have investigated a cold atom system with a time-independent order parameter, and derived the quantum transport equation which describes the temporal evolution of the quasiparticle number distribution.[2] Our transport equation contains an additional collision term which is overlooked in the other methods and which is traced back to our choice of an appropriate quasiparticle picture. Our additional collision term vanishes in the equilibrium limit if there is no Landau instability, but remains non-vanishing to prevent the system from equilibration if there is Landau instability. Thus our transport equation with the additional term predicts new behaviors of the unstable system.

Now we have extended our theory to the case with a time-dependent order parameter by expanding the field operator with the time-dependent complete set, naturally defined by the TDBdG equations.[3] The temporal evolution of the order parameter is determined self-consistently and simultaneously as that of the quasiparticle number distribution.[4] To illustrate the dynamics of the condensate decays with either the Landau instability or the dynamical one, we solve the equations numerically and discriminate the two instabilities.

[1] H. Umezawa, "*Advanced Field Theory — Micro, Macro, and Thermal Physics*" (AIP, New York, 1993).
[2] Y. Nakamura, T. Sunaga, M. Mine, M. Okumura, and Y. Yamanaka, Ann. Phys. (N.Y.) **325**, 426 (2010).
[3] H Matsumoto and S. Sakamoto, Prog. Theor. Phys. **105**, 573 (2001); *ibid.*, **107**, 679 (2002).
[4] H. Chu and H. Umezawa, Int. J. Mod. Phys. A **9**, 1703 (1994); *ibid.*, **9**, 2363 (1994); *ibid.*, **10**, 1693 (1995).

Measuring entanglement in twin well condensates

C.V. Chianca, M.K. Olsen

ARC Centre of Excellence for Quantum-Atom Optics, School of Mathematics and Physics, University of Queensland, Queensland 4072, Australia.

It seems intuitively obvious that a tunnel-coupled two-well Bose -Einstein condensate will exhibit entanglement between the atomic ensembles in each well. In this work we show how it is surprisingly difficult to prove the existence of this entanglement without access to the full density matrix, which would be difficult for such a dynamical system. We consider many of the canonical inequalities which are used for continuous-variable systems, such as the Duan-Simon criterion [1], the Reid EPR criterion [2], the logarithmic negativity [3], and the generalised purity [4].

Using the truncated Wigner representation, we investigate these correlations with different initial number distributions and different initial quantum states, finding that all would be difficult to use and that none give a clear signal of the entanglement that one may reasonably expect to be present. The generalised purity is perhaps the least suitable, as it can indicate the presence of entanglement for two modes which have never interacted and are hence completely separable. We explain the difficulties encountered and comment on the relevance of the "death of entanglement"phenomenon to this system [5].

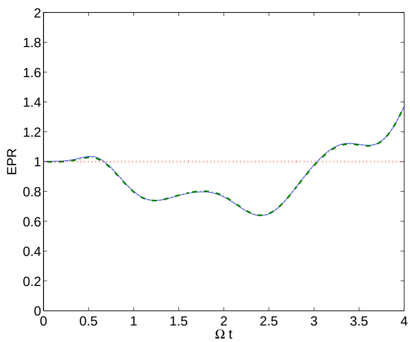


Figure 1: *The Reid EPR correlation for a twin-well condensate whose initial state is two independent coherent states, each with an average of 50 atoms, with time parametrised by the tunneling strength Ω. A value of less than one is clear evidence of entanglement.*

[1] L.-M. Duan, G. Giedke, J.I. Cirac, and P. Zoller, Phys. Rev. Lett. 84, 2722 (2000); R. Simon, Phys. Rev. Lett. 84, 2726 (2000)

[2] M.D. Reid, Phys. Rev. A 40, 913 (1989)

[3] G. Vidal and R.F. Werner, Phys. Rev. A 65, 032314 (2002)

[4] T. F. Viscondi, K. Furuya, and M. C. de Oliveira, Phys. Rev. A 80, 013610 (2009)

[5] T. Yu, J. H. Eberly, Phys. Rev. Lett. 97, 140403 (2006)

One-dimensional Bose gases in and out of equilibrium

A. Perrin, R.. Bücker, S. Manz, T. Betz, T. Berrada, T. Schumm, J. Schmiedmayer

Institute of Atomic and Subatomic Physics, Vienna University of Technology, Stadionallee 2, 1020 Vienna, Austria

Dimensionality strongly affect the physics of a Bose gas. Freezing its transverse degrees of freedom allows to enter the one-dimensional regime, characterized by large phase fluctuations for degenerate weakly interacting gases. In expansion, these fluctuations lead to strong density density correlations that we have been able to measure experimentally [1]. Our results show good agreement with a recent theoretical description [2]. Interestingly, our measurements take place in a near field regime where anomalous correlations play an important role.

Even though all the atoms forming a one-dimensional Bose gas lie in their transverse ground state, these degrees of freedom have to be taken into account to accurately describe the dynamics of such systems [3]. Populating their transverse excited states by parametric heating, we have been able to study their relaxation properties. Due to parity rules the decay by binary collisions of the transverse excitations leads to the creation of pairs of longitudinal high energy free particles with opposite momenta. Using a novel fluorescence detector [4], we have been able to show that the number difference of these modes is squeezed. We now aim to study the longitudinal relaxation of these correlated pairs.

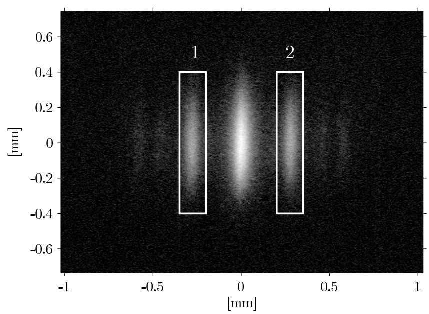


Figure 1: *View of a 1D quasicondensate after transverse parametric heating. On each of its sides one can distinguish highly excited longitudinal modes of the system. They originate from the decay of transverse excitations into longitudinal modes.*

[1] S. Manz, R. Bücker, T. Betz, C. Koller, S. Hofferberth, I. E. Mazets, A. Imambekov, E. Demler, A. Perrin, J. Schmiedmayer and T. Schumm, Phys. Rev. A **81**, 031610 (2010).

[2] A. Imambekov, I. E. Mazets, D. S. Petrov, V. Gritsev, S. Manz, S. Hofferberth, T. Schumm, E. Demler and J. Schmiedmayer, Phys. Rev. A **80**, 033604 (2009).

[3] I. E. Mazets, T. Schumm and J. Schmiedmayer, Phys. Rev. Lett. **100**, 210403 (2008).

[4] R. Bücker, A. Perrin, S. Manz, T. Betz, C. Koller, T. Plisson, J. Rottmann, T. Schumm and J. Schmiedmayer, NJP **11**, 103039 (2009).

Comparison of Finite Temperature Bose Gas Theories

S.P. Cockburn[1], A. Negretti[2], N.P. Proukakis[1], C. Henkel[3]

[1] *School of Mathematics and Statistics, University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU, United Kingdom*
[2] *Institute for Quantum Information Processing, University of Ulm, Albert- Einstein-Allee 11, D-89069 Ulm, Germany*
[3] *Institut für Physik, Universität Potsdam, Karl-Liebknecht-Str. 24-25, D-14476 Potsdam, Germany*

We present a detailed comparison of the equilibrium properties (density profiles, correlation functions, condensate statistics) of finite temperature Bose gases predicted by two commonly used approaches, namely the Number-Conserving Bogoliubov (NCB) [1] method versus the Stochastic Gross-Pitaevskii Equation (SGPE) [2]. We show that while their predictions agree at low temperatures, the well-known rethermalization problem of the NCB method, arising from the lack of self-consistency in the excited mode populations, leads to a noticeable breakdown of this method already at relatively small condensate depletion, significantly restricting its validity, a problem not encountered by the SGPE, which leads to the generation of a static thermal cloud distribution (within the restrictions of the classical approximation); on the other hand, the SGPE fails to predict the correct condensate statistics for very small atom number, due to its grand-canonical ensemble construction. Our results for density profiles and condensate statistics are also compared to those of Andersen *et al.* [3], and Scully and Svidzinsky [4].

We find the SGPE to be a more robust method for finite temperature equilibrium properties (except for very small N), and comment on the dynamical extension of our findings.

Acknowledgments: EPSRC, SCALA, DFG for funding; A. Sinatra, Y. Castin, U.V. Poulsen for discussions on the NCB.

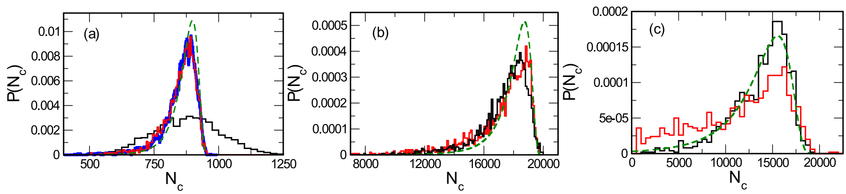


Figure 1: *Summary of regimes of applicability based upon condensate statistics for SGPE (black), NCB (solid grey) and Ref. [4] (dashed) with (a)* $N \sim 1000$ *and* $T \approx 0.23T_{1d}$, $N \sim 20000$ *and (b)* $T \approx 0.074T_{1d}$ *or (c)* $T \approx 0.23T_{1d}$.

[1] A. Sinatra , C. Lobo and Y. Castin, J. Phys. B: At. Mol. Opt. Phys. 35 3599 (2002).
[2] H.T.C. Stoof and M.J. Bijlsma, J. Low Temp. Phys. 124, 431 (2001); C.W Gardiner and M.J. Davis, J. Phys. B: At. Mol. Opt. Phys. 36 4731 (2003).
[3] U. Al Khawaja, J.O. Andersen, N.P. Proukakis, and H.T.C Stoof Phys. Rev. A 66, 013615 (2002).
[4] A.A. Svidzinsky and M.O. Scully, Phys. Rev. Lett. 97, 190402 (2006).

Shot-to-Shot Variations in Dark Soliton Trajectories

S.P. Cockburn[1], N.P. Proukakis[1], H.E. Nistazakis[2], D.J. Frantzeskakis[2], T.P. Horikis[3], P.G. Kevrekidis[4]

[1]*School of Mathematics and Statistics, University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU, United Kingdom*
[2]*Department of Physics, University of Athens, Panepistimioupolis, Zografos, Athens 15784, Greece*
[3]*Department of Mathematics, University of Ioannina, Ioannina 45110, Greece*
[4]*Department of Mathematics and Statistics, University of Massachusetts, Amherst, Massachusetts 01003-4515, USA*

How do shot-to-shot variations affect the dynamics of dark solitons in weakly-interacting atomic Bose gases? A recent experiment[1] found some very long-lived trajectories, as compared to the average soliton lifetimes. We enhance this effect by studying a regime not yet probed by soliton experiments, namely that of a phase-fluctuating condensate: Simulations with the Stochastic Gross-Pitaevskii equation[2] in the limit $T_\phi \ll T \ll T_c$ reveal very large deviations in the trajectories of *individual* solitons, even when the solitons are introduced in an *identical* manner, an effect amplified for deeper solitons and at higher temperatures. This leads to a broad distribution of soliton decay times over the stochastic ensemble of soliton trajectories probed [3], and restricts the average trajectory to times much shorter times than the timescale of decay of a *single* trajectory. The *average* decay time is also captured analytically and by a Dissipative Gross-Pitaevskii Equation (DGPE) with *ab initio* calculated damping.

Funding: EPSRC, NSF, University of Athens S.A.R.G.

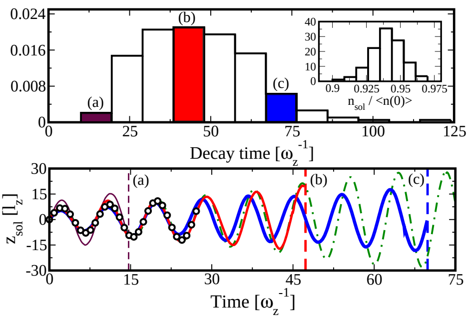


Figure 1: *Top: Normalized histograms of soliton decay times (main) and initial soliton depth (inset), n_{sol}. Bottom: Individual stochastic trajectories from marked histogram bins, 10-realization average (circles) and DGPE trajectory (dash-dotted).*

[1]C. Becker *et al.*, Nature Phys. 4, 496 (2008).
[2]H.T.C. Stoof and M.J. Bijlsma, J. Low Temp. Phys. 124, 431 (2001).
[3]S.P. Cockburn *et al.*, Phys. Rev. Lett. **104**, 174101 (2010)

How do Gaussian Anharmonicities Affect Soliton Dynamics?: The role of soliton-sound interactions

N.G. Parker[1,2,3], C.S. Adams[1], A.J. Allen[4], D. Jackson[4], C.F. Barenghi[4], N.P. Proukakis[1,4]

[1]*Department of Physics, Durham University, Durham DH1 3LE, United Kingdom*
[2]*School of Food Science and Nutrition, University of Leeds, Leeds LS2 9JT, U.K.*
[3]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada*
[4]*School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom*

Recent experiments with pure atomic Bose-Einstein condensates have confirmed the predicted dark soliton oscillations when under harmonic trapping[1]. However, a dark soliton propagating in an inhomogeneous condensate is unstable to the emission of sound waves[2]. Although harmonic trapping supports an equilibrium between the co-existing soliton and sound, we show[3] that the ensuing dynamics are sensitive to trap anharmonicities, even those arising in typical optical dipole traps. Such anharmonicities can break the soliton-sound equilibrium and lead to the net decay of the soliton on a *considerably shorter* time scale than other dissipation mechanisms, an effect that should be directly observable under current experimental conditions. We also report on a range of interesting effects when more than one solitons are present in the system[4].

We acknowledge funding from the EPSRC and the Canadian government.

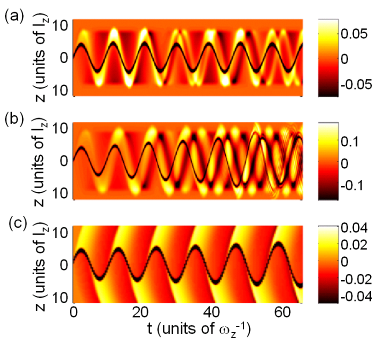


Figure 1: *Space-time plots of renormalised density (i.e. with the background subtracted) showing the dynamics of a $v_0 = 0.5c$ dark soliton in a (a) deep gaussian trap, (b) shallow gaussian trap ($V_0 = 2\mu$), and (c) infinite 'closed' system.*

[1]A. Weller *et al.*, Phys. Rev. Lett. 101, 130401 (2008); C. Becker em et al., Nat. Phys. 4, 496 (2008).
[2]N. G. Parker, N. P. Proukakis, M. Leadbeater, and C. S. Adams, Phys. Rev. Lett. 90, 220401 (2003).
[3]N.G. Parker, N.P. Proukakis, and C.S. Adams, Phys. Rev. A 81, 033606 (2010).
[4]A.J. Allen, D. Jackson, C.F. Barenghi, and N.P. Proukakis (Preprint)

Enhanced and reduced atom number fluctuations in a BEC splitter

K Maussang[1], G. E. Marti[2], T. Schneider[3], P. Treutlein[4], Y. Li[1,5], A. Sinatra[1], R. Long[1], Jérôme Estève[1], Jakob Reichel[1]

[1]*Laboratoire Kastler Brossel, CNRS – ENS – UPMC/Université Paris 6, Paris, France*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Institut für Experimentalphysik, Heinrich Heine Universität, 40225 Düsseldorf, Germany*
[4]*Departement Physik, Universität Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[5]*Precision Spectroscopy, Department of Physics, East China Normal University, Shanghai 200062, China*

We measure atom number statistics after splitting a gas of ultracold ^{87}Rb atoms in a purely magnetic double-well potential created on an atom chip. Well below the critical temperature for Bose-Einstein condensation T_c, we observe reduced fluctuations down to $-4.9\,\mathrm{dB}$ below the atom shot noise level. Fluctuations rise to more than $+3.8\,\mathrm{dB}$ close to T_c, before reaching the shot noise level for higher temperatures. We use two-mode and classical field simulations to model these results. This allows us to confirm that the super-shot noise fluctuations directly originate from quantum statistics.

Scattering effects in the dynamics of a cold Bose gas

L. Rico-Perez, J.R. Anglin

Technische Universitaet Kaiserslautern, Kaiserslautern, Germany

We address the problem of the emergence of classical behavior in cold Bose gases, focusing in the role played by weak interactions in the transition from the purely quantum regime into the classical one. Departing from elemental scattering calculations we develop a time evolution equation for the reduced one particle density matrix of the gas. Taking into account only the effect of s-wave scattering processes, the model drives to a clearly analogous to the Stosszahl Ansatz introduced by Boltzmann in the statistical description of gases in the classical regime. We explore numerically the simplified one dimensional version of the model in order to understand the impact of interactions in tunneling processes beyond the mean field Gross-Pitaevskii approach. We expect the model to help in the comprehension of other relevant processes in cold Bose gases experiments, specially the arise of decoherence.