Quantum Technologies Conference

Manipulating photons, atoms, and molecules

Abstract Booklet

© Adam Łowicki, Młody Technik

Last update: 24.08.2010

August 29 – September 3, 2010, Toruń, Poland

Slow and stationary light in atomic media

Gediminas Juzeliunas

Institute of Theoretical Physics and Astronomy, Vilnius University, Lithuania

During the last several years there has been a great deal of interest in slow and stationary light propagating in resonant atomic media under the influence of one or several light beams of higher intensities (to be referred to as the control beams). Yet the existing studies restrict to slow and stationary light which can be described in terms of a single component field. In the present talk we shall first review the usual slow and stationary light. Subsequently we shall analyse a setup involving two pairs of counter-propagating control laser beams. This enables one to create two-component slow or stationary light exhibiting a number of distinct properties, such as the neutrino type oscillations between the components. Under certain conditions the two-component slow light can be described by a relativistic equation of the Dirac-type for a particle of a finite mass. This leads to the “particle-antiparticle” dispersion branches separated by an energy gap D. The corresponding Compton length L=v/D determines the tunneling length of probe light though the sample, v being the “ultra-relativistic” velocity of the slow light.

Spin dipole oscillations of strongly interacting normal Fermi gases

Alessio Recati and Sandro Stringari

CNR-INO BEC Center, Università di Trento,

Via Sommarive 14 I-38123 Povo, Italy

In the recent years degenerate fermionic atoms have became available in many laboratories. The possibility of trapping two (or more) species with tunable interaction have made them a nice playground to study many-body effects, as, e.g., superfluid pairing. Recently two new normal phases in Fermi-1/2 systems have been attracted a lot of interest: a strongly attractive polarized gas and a repulsive interacting gas.

We discuss spin-dipole oscillations of such systems and point out that they provide information on the property of the system and can be a crucialtest for the theories describing them.

In the first part using density functional theory in a time dependent approach we determine the frequencies of the compressional modes of the normal phase of a Fermi gasat unitarity as a function of its polarization. Our energy functional accounts for the typical elastic deformations exhibited by Landau theory of Fermi liquids. The comparison with the available experiments is biased by important collisional effects affecting both the "in phase" and the "out of phase" oscillations even at the lowest temperatures. New experiments in the collisionless regime would provide a crucial test of the applicability of Landau theory to the dynamics of these strongly interacting normal Fermi gases.

In the second part we discuss the role played by the magnetic susceptibility in characterizing the spin fluctuations and the dynamic behavior of a trapped Fermi gas interacting with repulsive forces. Using a sum rule approach and recent Monte Carlo results for the magnetic susceptibility of uniform matter we provide explicit resultsfor the spin dipole oscillation in presence of harmonic trapping. We show that even below the transition to the ferromagnetic phase the dipole frequency exhibits significant deviations from the ideal gas behaviour.

Unconventional superfluidity of fermions in Bose-Fermi mixtures

Omjyoti Dutta
ICFO-Institut de Ciències Fotòniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain.

ABSTRACT

Experimental realization of fermionic superfluidity in a quantum degenerate ultracold gas started a renewed interest in the field. Attraction between fermionic particles favours pairing of fermions resulting in superfluidity of the system. The paired fermions, known as Cooper pairs, can have different kinds of internal symmetries. The common ones found in nature have s-wave and d-wave internal structure and conserve parity and time reversal symmetry. In superfluid ^{3}He, the so-called A and A_1 phases are characterized by Cooper pairs with nonzero magnetic orbital momenta. Cooper pairs with chiral $p_x + ip_y$-wave internal structure are believed to be responsible for the observed superfluidity of electrons in Strontium Ruthenate. When confined in a two dimensional geometry, excitations in the chiral p-wave superfluid become so called non-Abelian anyons. Apart from fundamental interest in the existence of such particles, non-Abelian anyons find remarkable applications in the field of quantum information for quantum memories and fault-tolerant quantum computation

Recently it has been shown that quasi-particles in vortex excitations of chiral two-dimensional p-wave spinless superfluids obey non-Abelian statistics. Using p-wave Feshbach resonances in fermionic ultracold atoms, such superfluids can be realized in principle, but this procedure is very difficult because of non-elastic loss processes. Bose-Fermi mixtures are another candidate for creating superfluidity in fermions via boson mediated interactions and have formal resemblance to phonon mediated superconductivity in metals. It was found, however, when the bosons and single-component fermions are completely mixed, increasing the boson-fermion interaction strength, or fermionic density may induce dynamical instability of the condensate resulting in phase separation between the mixture. Near phase separation, inclusion of the dressing of phonons is predicted to increase the transition temperature.

In the present paper, we discuss another way to generate high temperature superfluids in a Bose-Fermi mixture. We study the property of superfluidity in Bose-Fermi mixtures, where bosons are interacting via long-ranged dipolar interactions. We show that the transition temperature for p-wave superfluidity can become comparable to the Fermi energy. More importantly, we find that other more exotic Cooper pairs with f- and h-wave internal symmetries are possible in certain range of Fermi energies without bosons and fermions separating. In addition, we study the excitations in chiral states of the odd-wave superfluids and point out their non-Abelian anyonic nature. Experimentally, an available bosonic species, where prominent dipolar interaction can be achieved using Feshbach resonance is Cr^{52}. Another route towards achieving ultracold dipolar gas is to experimentally realize quantum degenerate heteronuclear molecules, which have permanent electric moment. Thus, in the near future a quantum degenerate mixture of dipolar bosons and fermions will be achievable experimentally.

We examine two dimensional mixture of single-component fermions and dipolar bosons[1]. First we study the boson-fermion interaction and the many-body effect of fermions on dressing the excitation spectrum of the condensate. We go beyond Migdal's limit and include first order vertex corrections to study fermion self-energy in normal chennel as well as in the Cooper pair channel. In doing so, we include the full effect of retardation and strong momentum dependance of the bosonic excitation spectrum and bosonic propagator. By deriving a vertex-corrected strong-coupling Eliashberg equation, we predict that the vertex-corrected mechanism supports superfluids with p, f and h-wave pairing symmetries at experimentally feasible transition temperatureswe solve for transition temperatures in different angular momentum channels. further, we present a brief discussion regarding the possible occurrence of non-Abelian Majorana fermions for broken time-reversal p, f, and h-wave superfluids. We solve the Bugoliubov-deGennes equation for the p, f, and h-wave superfluids in the limit of large distance to find the Majorana bound states.

---

[1] Unconventional superfluidity of fermions in Bose-Fermi mixtures, O. Dutta, and M. Lewenstein, arXiv:1003.0329.

THE FOUNTAIN EFFECT IN A BOSE-EINSTEIN CONDENSATE

Tomasz Karpiuk [1], Benoît Grémaud [1,2,3], Christian Miniatura [1,2,4], Mariusz Gajda [5,6], and Berthold-Georg Englert [1,2]

[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 PAN, Aleja Lotników 32/46, 02-668 Warsaw, Poland, [6] WMP-SNŚ, UKSW, Warsaw, Poland

Keywords: superfluidity, the fountain effect, the thermomechanical effect, the classical field approximation

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).

Superluminal pulse propagation in multi-level optically dressed atomic system

P. Grochowska[1], A. Raczynski[1], J. Zaremba[1], S. Zielinska-Kaniasty[2]

[1] *Instytut Fizyki, Uniwersytet Mikołaja Kopernika, ul. Grudziadzka 5,87-100, Torun, Poland*
[2] *Instytut Matematyki i Fizyki, Uniwersytet Technologiczno – Przyrodniczy, al. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland*

We analyze the propagation of a probe laser pulse in a four-level atomic system with two closely spaced upper levels. The optical properties of the system are modified by a strong coupling field and possibly by an incoherent pump so that the medium may have alternatively absorptive or gain properties. The electric susceptibility is modified, leading to a change of the group velocity both in sub- and superluminal regimes.

The regimes of parameters are especially investigated in which absorption (gain) is not too strong, with dispersion being not too steep. The dynamics of propagation is studied in detail, in particular in the case of negative group velocities of a small absolute value.

Keywords: superluminal, group velocity, electric susceptibility, pulse propagation

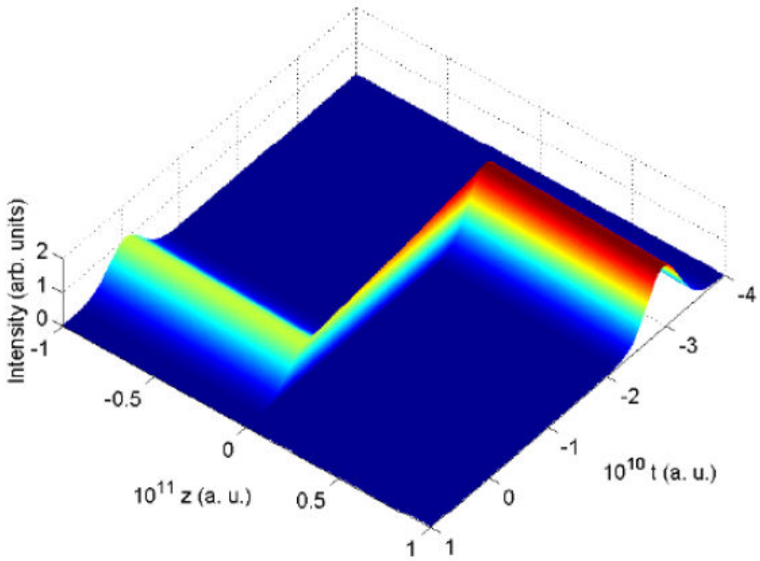

Figure 1: A typical space-time plot of a pulse propagation for a negative group velocity. Distances and times are given in atom units. Initial pulse duration is $\tau=1.4\cdot10^9$. The medium extends from $z = 0$ to $1\cdot10^9$. The susceptibility obtained in our model with gain is, in the interval of interest, given by $\chi(\omega) = -4.2\cdot10^4\ \omega - i\cdot8\cdot10^{-7}$. Note a large time advance of the secondary pulse formation at the end of the sample.

Relative number squeezing in atomic spontaneous four wave mixing

M.Bonneau(1), J.-C.Jaskula(1), V.Krachmalnicoff(1), G.B.Partridge(1), A.Aspect(1), D.Boiron(1), C.I.Westbrook(1), K.V.Kheruntsyan(2), P.Deuar(3)

(1) Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Univ Paris-sud, Palaiseau, France
(2) ARC Centre of Excellence for Quantum-Atom Optics, University of Queensland, Brisbane, Australia
(3) Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

We performed atomic SFWM through the collision of 2 Bose Einstein condensates (BEC) of metastable helium. We thus generated pairs of scattered atoms, which have opposite momenta and lie on a shell whose diameter is given to first order by the velocity difference of the BECs. This atomic source should have similar quantum properties as the parametric down conversion source widely used in quantum optics. We already demonstrated [1]correlation of atoms with opposite velocity, as expected for the created pairs, and of atoms with colinear velocity, due to the Hanbury Brown and Twiss effect. We will present here the observation of relative number squeezing in such an experiment: The atomic shell is reconstructed with a 3D single particle detector. We then exclude the BECs and cut the shell into n slices. For each pair of slices (i, j), we considere the atom number difference $N_i - N_j$. For uncorrelated atoms, the variance V_{ij} of this quantity is expected to be Poissonian, $V_{i,j} = \langle N_i + N_j \rangle$, whereas it should be subpoissonian for correlated ones.
We measured 10% diminution of the normalized variance for opposite slices, and verified that there is no squeezing for other combinaisons (fig 1a). The measured squeezing is limited by the quantum efficiency of our detector (about 13%). Another limitation is the finite width of the 2-particle correlation function: if one atom is detected in slice i near a border, there is a non-zero probability for its partner to be detected in the slice next to the one opposite to i. This last effect increases with the number of slices n, as shown on figure 1b.

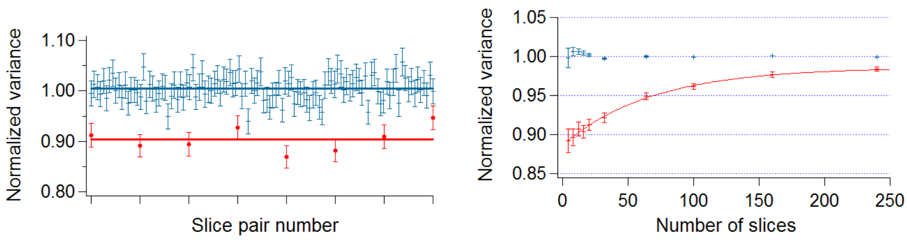

Figure 1: (a)Normalized variance $V_{i,j}/\langle N_i + N_j \rangle$ of all pairs of slices (i, j). The scattering halo has been divided in $n = 16$ slices. The normalized variance for the 8 correlated slice pairs (in red) has an average value of 0.904(8) whereas it is 1.005(2) for the uncorrelated ones (in blue). (b)Normalized variance in function of the number of slices n.

[1]A. Perrin, H. Chang, V. Krachmalnicoff, M. Schellekens, D. Boiron, A. Aspect, C. I. Westbrook, Phys. Rev. Lett. **99**, 150405 (2007).

Quantifying interacting dark states through higher order probe response

Preethi T.M., Manukumara M. and A. Narayanan

May 28, 2010

Creation of Coherent Population Trapped (CPT) states using laser light and atomic ensembles has become the central idea behind many novel quantum optical phenomena like Electromagnetically Induced Transparency (EIT) and coherent non-linear optics. In recent years this idea has been used for faithful transfer of classical and quantum correlations between matter and light during resonant light matter interaction.

In resonant light interaction with hyperfine atomic levels of alkali atoms at room temperature, the separation of energy levels are within the Doppler width and typically multiple CPT (dark) states are created. These states interact with each other coherently and this interaction serves to increase the spectral domain of dark states. In this talk we demonstrate an experimental scheme for non-invasive tracking and quantification of interaction between multiple dark states.

Our level scheme is centered around the D2 line of ^{87}Rb. We work with a double Λ system with the two ground states made up of $m_F = -1$ and $m_F = +1$ of $F = 1$ in $5S_{1/2}$ and with the two excited states as $5P_{3/2}, F = 0'$ and $5P_{3/2}, F = 1'$. This degenerate double Λ system is irradiated with three fields with identical frequencies. The two fields L1 and L2 are co-propagating and produce the two dark states of the individual Λ systems. The L3 probe laser counter-propagates to L1 and L2. The L1 beam is strong and the L2 and L3 beams have equal low intensities. The L1, L2 and L3 laser photons together satisfy a three photon resonance condition, which, under the two photon condition for L1 and L2 reduces to a velocity selective absorption condition for L3. Thus, the L3 absorption tracks the resultant of the two CPT states formed by L1 and L2 without itself taking part in this effect.

We see that the contrast of absorption in L3 shows a periodic variation as a function of laser detuning δ_p from $0'$. We will show during this talk that the minima are spectral positions where the transition probability to $0'$ and $1'$ from the common ground state is equal. We also show that these are the detunings at which the interaction between the two CPT states is partially destructive. We further show that the position of minima (or maxima) do not vary for an order of magnitude variation in the intensity of the strong laser L1.

The absorption contrast in the L3 beam thus serves as a marker for mapping the entire domain of interacting dark states. By properly calibrating the absorption contrast, we could identify spectral positions of maximum destructive and constructive interactions between two dark states. We envisage that this might be a valuable tool for finding out the fidelity of engineered quantum states.

ADIABATIC TRAP DEFORMATION FOR PREPARING QUANTUM HALL STATES

M. Roncaglia[1], M. Rizzi[2], J. Dalibard[3]

[1]ISI Foundation, Villa Gualino, viale Settimio Severo 65
I-10133 Torino, Italy
[2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1
D-85748, Garching, Germany
[3]Laboratoire Kastler Brossel, Département de Physique de l'École Normale Supérieure,
24 rue Lhomond, 75005 Paris, France

One of the biggest challenges in physics of trapped ultracold atoms is the observation of the quantum Hall effect (QHE), when a gas of bosonic atoms is put in rapid rotation. A considerable experimental effort have been spent in this direction, but some fundamental obstacles seem to prevent the gas from going beyond the vortex-lattice phase when rotation is generated by stirring the gas inside a harmonic trap. One of the main obstacles consists in the difficulty of imparting to the system a sufficient amount of angular momentum. Here, we discuss and propose feasible schemes for preparing adiabatically quantum-Hall states starting from a gas initially confined in a ring by using a "Mexican-hat" potential with a strong bump at the center. Setting a given rotation speed of the ring, it is possible to inject into the atomic gas an appropriate quantity of angular momentum, stored in the form of a giant vortex state. Afterwards, the potential is adiabatically deformed into a harmonic trap. We provide clear numerical evidence that the interacting bosonic gas in the ring for some precise values of angular frequency is indeed adiabatically connected with known quantum-Hall states, like the $\nu=1/2$ Laughlin or the $\nu=1$ Pfaffian.

NONLINEAR PHASE SHIFTS IN A PERIODICALLY DRESSED TRIPOD ATOMIC MEDIUM

K. Słowik[1],M.Artoni[2,3],G. La Rocca[4],A. Raczyński[1], J. Zaremba[1],S. Zielińska-Kaniasty[5]

[1]Department of Physics, Astronomy and Applied Informatics, Nicolaus Copernicus University, Toruń, Poland

[2]Department of Physics and Chemistry of Materials, Brescia University, Brescia, Italy

[3]LENS, Firenze, Italy

[4]Scuola Normale Superiore and CNISM, Pisa, Italy

[5]Institute of Mathematics and Physics, University of Technology and Life Sciences, Bydgoszcz, Poland

A simultaneous propagation of two pulses in an atomic medium in the tripod configuration is studied. The medium is optically dressed by a strong standing wave. Due to the periodic structure of the dressed susceptibility both propagating fields acquire their reflected components. Nonlinear cross propagation effects (cross Kerr nonlinearities) are analyzed: each of propagating fields experiences quadratic corrections to the susceptibility due to other field. Regions of parameters are sought in which nonlinear phase shifts of the transmitted and reflected components of both pulses are large. The nonlinear phase shifts for the transmitted pulses are compared with those in the running-wave case. A possible realization of a polarization phase gate is studied.

Light-induced Gauge Potentials for Cold Atoms

Julius Ruseckas and Gediminas Juzeliūnas
Institute of Theoretical Physics and Astronomy, Vilnius University,
Vilnius, Lithuania

In the initial part of the presentation we review the schemes enabling to produce the artificial magnetic field for cold atoms using several light beams are reviewed. We discuss the possibilities to create both the Abelian and also non-Abelian [1-6] gauge potentials. Subsequently we shall present some recent studies of the effects due to the non-Abelian gauge potentials for cold atoms including their quasi-relativistic behaviour [1-3] and negative reflection [4]. In the final part we shall present our latest work [5] on generating the non-Abelian gauge potentials for cold atoms containing three degenerate dressed states, so their centre of mass motion is described by a three-component spinor.

[1] G. Juzeliūnas, J. Ruseckas, M. Lindberg, L. Santos, and P. Öhberg, Phys. Rev. A **77** 011802(R) (2008).
[2] J. Y. Vaishnav and C. W. Clark, Phys. Rev. Lett. **100**, 153002 (2008) . [3] M. Merkl, F. E. Zimmer, G. Juzeliunas and P. Öhberg, Europhys. Lett. **83**, 54002 (2008).
[4] G. Juzeliūnas, J. Ruseckas, A. Jacob, L. Santos, P. Öhberg, Phys. Rev. Lett. **100**, 200405 (2008).
[5] G. Juzeliūnas, J. Ruseckas and J. Dalibard, Phys. Rev. A **81**, 053403 (2010).
[6] J. Ruseckas, G. Juzeliūnas, P. Öhberg, and M. Fleischhauer, Phys. Rev. Lett. **95**, 010404 (2005).

Correlation and Entanglement of Multipartite States

Y. B. Band and I. Osherov

Departments of Chemistry and Electro-Optics and the IlseKatz Center for Nano-Science, Ben-Gurion University, Beer-Sheva 84105, Israel

We derive a classification and a measure of classical- andquantum-correlation of multipartite qubit, qutrit, ..., and, ingeneral, n-level systems, in terms of SU(n) representations of densitymatrices. We relate these to entanglement.The characterization of correlation is developed in terms of thenumber of nonzero singular values of the correlation matrices thatparameterize the density matrix.The characterization of entanglement includes additional invariantparameters of the density matrix ρ.We apply the formalism to calculate atomic clock collisional shifts.

Useful quantum states in the presence of classical noise in a Bose Josephson junction

G. Ferrini,[1] D. Spehner,[1,2] A. Minguzzi,[1] and F.W.J. Hekking[1]

[1]*Université Joseph Fourier, Laboratoire de Physique et Modélisation des Mileux Condensés, C.N.R.S. B.P. 166, 38042 Grenoble, France*

[2]*Institut Fourier, Université Joseph Fourier, B.P. 74, 38402 Saint Martin D'Hérès, France*

We study the dynamical production of quantum states useful for interferometry in a Bose Josephson junction, in the presence of noise. After a sudden quench, the dynamics is driven by the interatomic interactions, which lead to the formation of useful entangled states (e.g. squeezed states at short times, macroscopic superpositions at larger times). Such states can be employed in interferometric applications to overcome classical limits of precision [1–3]. The presence of noise degrades these useful quantum correlations. In particular, we consider the effect induced by stochastic fluctuations of the energy of the two-modes [4]. We study such effect on squeezed states, and compare our results to the experiments [3]. Then we address the decoherence of macroscopic superpositions and show that these latter are quite robust with respect to the noise considered, as the decoherence rate does not depend on the total number of particles. Finally, we identify the regime of parameters and the optimum time for the production of useful quantum states by calculating the squeezing and the quantum Fisher information.

---

[1] D.J. Wineland *et al.*, Phys. Rev. A **50**, 67 (1994).
[2] L. Pezzé and A. Smerzi, Phys. Rev. Lett. **102**, 100401 (2009).
[3] C. Gross *et al.*, Nature **464**, 1165 (2010).
[4] G. Ferrini, D. Spehner, A. Minguzzi and F.W.J. Hekking, arXiv:0911.0655.

Complete devil's staircase and crystal–superfluid transitions in a dipolar XXZ spin chain: A trapped ion quantum simulation

Philipp Hauke,[1,*] Fernando M. Cucchietti,[1] Alexander Müller-Hermes,[2]
Mari-Carmen Bañuls,[2] Ignacio Cirac,[2] and Maciej Lewenstein[1]

[1] ICFO – Institut de Ciències Fotòniques,
Mediterranean Technology Park, E-08860 Castelldefels (Barcelona), Spain
[2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany

(Dated: May 31, 2010)

Systems with long-range interactions show a variety of intriguing properties: their low-lying energy spectrum typically accommodates many meta-stable states, which may be useful as quantum memories, they can give rise to spontaneous formation of supersolid phases, and they can show counterintuitive thermodynamic behavior like superextensivity, breaking of ergodicity, or a non-concave entropy. However, theoretical studies are strongly hindered by the increased complexity of long-range interactions. Hence, having a quantum simulator for long-range models is highly desirable. Among these, models with dipolar interactions are of particular practical relevance, due to their common occurrence in nature. We show that a chain of trapped ions can be used to quantum simulate a one-dimensional model of hard-core bosons with dipolar off-site interaction and tunneling, a model which is equivalent to a dipolar XXZ spin-1/2 chain. We explore the rich phase diagram of this model in detail, employing analytical approximate methods (perturbative mean-field theory, Gutzwiller mean-field theory), exact diagonalization, and quasi-exact numerical techniques (density-matrix renormalization group, infinite time evolving block decimation). We find that the complete devil's staircase – a succession of crystal states existing at vanishing tunneling – spreads to a succession of lobes similar to the Mott-lobes found in Bose–Hubbard models. Further, we investigate the melting of these crystal states at increased tunneling. Contrary to similar two-dimensional models, we do not find any clear indications of supersolid behavior in the transition region between the crystal and the superfluid phases.

---

* Electronic address: `Philipp.Hauke@icfo.es`

Sub shot-noise interferometry and multiparticle entanglement

Philipp Hyllus[1], Luca Pezzé[2], Augusto Smerzi[1], Roland Krischek[3,4], Christian Schwemmer[3,4], Wiesław Laskowski[3,4,5], Witlef Wieczorek[3,4,6], and Harald Weinfurter[3,4]
[1] *INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, I-38123 Povo, Italy*
[2] *Laboratoire Charles Fabry, Institut d'Optique, 91127 Palaiseau, France*
[3] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany*
[4] *Department für Physik, Ludwig-Maximilians-Universität, D-80797 München, Germany*
[5] *Institute of Theoretical Physics and Astrophysics, University of Gdansk, ul. Wita Stwosza 57, 80-952 Gdanks, Poland*
[6] *Faculty of Physics, University of Vienna, Boltzmanngasse 3, 1090 Wien, Austria*

Entangled quantum states allow for sub shot-noise sensitivity with linear interferometers [1–3], with applications in various fields such as quantum frequency standards, quantum lithography, quantum positioning and clock synchronization, and quantum imaging [4]. The possibility of reaching sub shot-noise sensitivity has has been demonstrated in experiments with entangled states of up to 8 photons [5–7], and up to 5 ions [8]. These works applied a linear error model to estimate the possible sensitivity. Here, we perform a full estimation protocol with a Bayesean strategy using a 4-photon twin-fock state [9], which can assign a meaningful phase error even to a single measurement. We demonstrate sub shot-noise sensitivity for a large range of phase shifts, and the connection to multipartite entanglement *via* the Fisher information, which is related to the optimal phase sensitivity achievable *via* the Cramer-Rao bound [10, 11]. This shows that the high sensitivity we observe in the experiment is connected to the presence of genuine 4-partite entanglement in the input state.

[1] V. Giovannetti, S. Lloyd, and L. Maccone, Phys. Rev. Lett. **96**, 010401 (2006).

[2] L. Pezzé and A. Smerzi, Phys. Rev. Lett. **102**, 100401 (2009).

[3] The connection between shot-noise limit and separability for a non-fixed number of particles has been discussed in P. Hyllus, L. Pezzé, and A. Smerzi, arXiv:1003.0649.

[4] V. Giovannetti, S. Lloyd, and L. Maccone, Science **306**, 1330 (2004).

[5] T. Nagata, R. Okamoto, J. L. O'Brien, K. Sasaki, and S. Takeuchi, Science **316**, 726 (2007).

[6] J. C. F. Matthews, A. Politi, A. Stefanov, and J. L. O'Brien, Nat. Phot. **3**, 346 (2009).

[7] W.-B. Gao *et al.*, C.-Y. Lu, X.-C. Yao, P. Xu, O. Gühne, A. Goebel, Y.-A. Chen, C.-Z. Peng, Z.-B. Chen, and J.-W. Pan, Nature Phys. **6**, 331 (2010).

[8] D. Leibfried, E. Knill, S. Seidelin, J. Britton, R. B. Blakestad, J. Chiaverini, D. B. Hume, W. M. Itano, J. Jost, C. Langer, et al., Nature (London) **438**, 639 (2005).

[9] M. J. Holland and K. Burnett, Phys. Rev. Lett. **71**, 1355 (1993).

[10] C. W. Helstrom, *Quantum Detection and Estimation Theory* (Academic Press, New York, 1976).

[11] A. S. Holevo, *Probabilistic and Statistical Aspects of Quantum Theory* (North-Holland, Amsterdam, 1982).

Entanglement swapping with artificial atoms

Marcin Kurpas and Elżbieta Zipper
Instytut Fizyki, Uniwersytet Śląski, ul. Uniwersytecka 4,
40-007 Katowice, Polska

Quantum entanglement is one of the most spectacular feature of quantum world. Besides its fascinating conceptual aspect it also plays an important role in quantum information processing i.e. it is essential for quantum state teleportation, dense coding, quantum cryptography etc. Among many methods of creation of entanglement, entanglement swapping [1] is of special importance as it allows the entanglement between particles that do not share common history. Despite the fact that originally it was proposed to entangle photons [1], it has been successfully utilized to entangle atomic [2] and quantum dot [3] systems.

The physics of atom-light interaction has been known since the beginning of the quantum theory. Nevertheless, the concept of quantum information processing has caused the revival of interest of this field. Atoms are good candidates for implementation of the quantum bits as they are identical and have exactly the same properties in fixed conditions e.g. the same resonant frequency. However, they have some disadvantages like the problem of scalability, atom-field interaction strength, which are not present in solid state systems called 'artificial atoms'.

Based on the experimental realization of entanglement swapping for atomic systems [2] we consider two artificial atoms, each independently coupled to a single-mode electromagnetic field within a quantum cavity [4]. The interaction of the atoms with the fields leads to entanglement of their sates. The projection of the photons leaving the cavities onto one on the Bell states entangles the qubits that have never interacted before. We show that for some conditions this method gives maximally entangled states of the qubits in each try of the measurement. We also take into account the influence of dissipation.

[1] M. Żukowski, A. Zeilinger, M.A. Horne, A.K. Ekert, Phys. Rev. Lett. **71**, 4287 (1993)
[2] D.L. Moehring, P. Maunz, S. Olmschenk, K.C. Younge, D.N. Matsukevich, L.M. Duan, C. Monroe, Nature **449**, 68 (2007)
[3] S.D. Barrett, P. Kok, Phys. Rev. A **71**, 060310(R) (2005)
[4] M. Kurpas and E. Zipper, Eur. Phys. Journ. D **50**, 201 (2008).

Towards electron-electron entanglement in Penning traps

L. Lamata, D. Porras, and J. I. Cirac
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
J. Goldman and G. Gabrielse
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Entanglement of isolated elementary particles other than photons has not yet been achieved. We show how building blocks demonstrated with one trapped electron might be used to make a model system and method for entangling two electrons. Applications are then considered, including two-qubit gates and more precise quantum metrology protocols.

Entanglement is one of the most remarkable features of quantum mechanics. Two entangled systems share the holistic property of nonseparability—their joint state cannot be expressed as a tensor product of individual states. Entanglement is also at the center of the rapidly developing field of quantum information science. A variety of systems have been entangled, including photons, ions, atoms, and superconducting qubits. However, no isolated elementary particles other than photons have been entangled. It is possible to perform quantum information protocols with electrons in Penning traps, as opposed to ions, even though the former cannot be laser cooled. This is possible because at low temperature in a large magnetic field (100 mK and 6 T in Harvard experiments [1]) the cyclotron motion radiatively cools to the ground state. We describe how one could use this mode for quantum information applications since there is sufficiently small coupling to other modes.

In this work, we describe a possible method for entangling two electrons [2]. The model system and method we investigate are largely based on building blocks already demonstrated with one trapped electron. On the way to measuring the electron's magnetic moment to 3 parts in 10^{13} [1], quantum nondemolition (QND) methods were used to reveal one quantum cyclotron and spin transitions between the lowest energy levels of a single electron suspended for months in a Penning trap. We demonstrate how the two-electron entanglement could make a universal two-qubit gate. We show how this gate could enable a metrology protocol that surpasses the shot-noise limit, and as an example we consider in detail the requirements for implementing this protocol in a measurement of the electron magnetic moment using two trapped entangled electrons. The payoffs and requirements for moving from two-electron to N-electron entanglement are listed. Possible applications include quantum simulators, analysis of decoherence, and more precise electron magnetic moment measurements using improved quantum metrology protocols.

[1] D. Hanneke, S. Fogwell, and G. Gabrielse, Phys. Rev. Lett. **100**, 120801 (2008).
[2] L. Lamata, D. Porras, J.I. Cirac, J. Goldman, and G. Gabrielse, Phys. Rev. A **81**, 022301 (2010).

K. Pawlowski, P. Bienias, K. Rzażewski,

STATISTICAL PROPERTIES OF ULTRACOLD ATOMS IN A 1D HARMONIC TRAP

Przemysław Bienias [1], Krzysztof Pawłowski [1], Mariusz Gajda [3], Emilia Witkowska [3] and Kazimierz Rzażewski [1,2]

[1] Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland,
[2] Faculty of Mathematics and Sciences, Cardinal Stefan Wyszyński University,
ul. Dewajtis 5, 01-815, Warsaw, Poland
[3] Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02-668 Warsaw, Poland

Keywords: bose gas, statistics

bose gas statistics

Altough the statistical properties of ultracold bosons have been of great interests of physicists for decades, even the choice of statistical ensemble was questionable until 90th. Here we use the classical field approximation (CFA). In this approximation the quantum field operator is replaced by its classical counterpart and the spectrum is restricted to the first $K + 1$ energy states. There exists the optimal cut-off K which allows to match the full probability distribution of the condensate population by its classical counterpart in the ideal gas case. Universal scaling of that cut-off with temperature and dimensionality was derived in [1]. We then, investigate the weakly interacting bosons using the Monte Carlo method. For the first time statistical properties of a one dimensional Bose gas in a trap are obtained with atom-atom interaction accounted for in all orders. Temperature dependence of the statistics of condensate population as well as low order spatial correlation functions are computed.

[1] E. Witkowska et al, Phys. Rev. A **79**, (2009) 033631.

Theory of Two-Component BEC Interferometry

B. J. Dalton[1] and B.M. Garraway[2]

Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia[1]
Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, UK[2]

Many previous treatments [1,2] for two component BEC interferometry are based on the simplest assumption that during the interferometric process the condensate is unfragmented, with all N bosons occupying the same single particle state. The latter is a linear superposition of two distinct single particle states (or modes), $\phi_F(\mathbf{r},t)|F\rangle$ and $\phi_G(\mathbf{r},t)|G\rangle$ that each boson could occupy - the internal states are $|F\rangle$, $|G\rangle$. The spatial wave functions $\phi_a(\mathbf{r},t)$ $(a = F,G)$ satisfy coupled Gross-Pitaevskii equations. However, in more general two mode theories (both for two component [3,4] BECs and single component [5,6,7] BECs with orthogonal spatial modes), the quantum state is a superposition with amplitudes $b_k(t)$ of Fock states with definite numbers $\frac{N}{2} \mp k$ of bosons in the two modes $(k = -\frac{N}{2},..,\frac{N}{2})$, unfragmented states just being a special case. Fragmentation effects (with two single particle states having macroscopic occupancy) have been found [7]. Spin angular momentum operators $\widehat{S}_\alpha$ $(\alpha = x,y,z)$ can also be defined for two mode systems, the Bloch vector components being their expectation values in units of N. All unfragmented states lie on the Bloch sphere of radius 1/2.

By applying the Dirac-Frenkel variational principle we derive matrix mechanics equations for the amplitudes $b_k(t)$ and generalized non-linear Gross-Pitaevskii equations for the mode functions $\phi_a(\mathbf{r},t)$. Self-consistent amplitude and mode equations are presented that are more general than expressions in [1,2], and differ from those in [3,4]. They can be used to treat various BEC interferometry experiments, such as Ramsey interferometry. Collisions may be ignored during the short coupling pulses, where the evolution is equivalent to rotations of the Bloch vector. During the collision only evolution, the magnitudes $|b_k(t)|$ of the amplitudes remain constant, but there is evolution of phase factors $A_k(t)$, where $b_k(t) = |b_k(t)|\exp(-iA_k(t)/\hbar)$. The Bloch vector undergoes Rabi oscillations and collision induced dephasing affects its x,y components.

If the spatial mode functions are assumed constant, the Hamiltonian can be described via the Josephson model, and a first approximation has been obtained for the amplitudes $b_k(t)$, enabling the evolution of the Bloch vector during the coupling $\widehat{H}_{Jos} \approx -J\widehat{S}_x$ and collision stages $\widehat{H}_{Jos} \approx \delta\widehat{S}_z + U\widehat{S}_z^2$ to be determined. Spin squeezing effects are also studied. Here J is the time-dependent coupling parameter and δ is the intercomponent transition energy. The collision parameter U may be enhanced by a large factor near a Feshbach resonance, increasing dephasing effects. If the Bloch vector no longer remains on the Bloch sphere, fragmentation effects will occur and the full generalised two mode theory would be required.

References

[1] P. B. Blakie, R. J. Ballagh and C. W. Gardiner, J. Opt. B **1**, 378, 1999

[2] R. P. Anderson, C. Ticknor, A. I. Sidorov and B. V. Hall, Phys. Rev. A **80**, 023603, 2009

[3] A. Sinatra and Y. Castin, Eur. Phys. J. D **8**, 319, 2000

[4] Y. Li, P. Treutlein, J. Reichel and A. Sinatra, Eur. Phys. J. B **68**, 365, 2009

[5] C. Menotti *et al*, Phys. Rev. A **63**, 023601, 2001

[6] B. J. Dalton, J. Mod Opt. **54**, 615, 2007

[7] O. E. Alon *et al*, Phys. Rev. A **77**, 033613, 2008

Restricted Thermalization and the Memory of Initial Conditions in Incompletely-Chaotic Quantum Systems

V. A. Yurovsky
School of Chemistry, Tel Aviv University

M. Olshanii
Department of Physics, University of Massachusetts Boston

A system consisting of two atoms in a circular, transversely harmonic waveguide in the multimode regime, interacting via a short-range potential, is analyzed [1]. It belongs to the class of problems where an integrable system is perturbed by a separable rank I interaction. The interaction couples every two waveguide eigenstates with the same strength, and thus does not obey any selection rules. Other representatives of this class are the Šeba billiard [2]—a flat two-dimensional rectangular billiard with a zero-range scatterer in the middle—and a system of two atoms with a zero-range interaction in a cylindrically-symmetric harmonic potential [3]. A common feature of the systems with separable interaction is the existence of an exact analytic solution, in spite of the absence of a complete set of integrals of motion. The systems do show some signatures of the quantum-chaotic behavior, although both the level statistics and the momentum distributions in individual eigenstates show substantial deviations from the quantum chaos predictions.

For the waveguide system, we study both the degree of the eigenstate thermalization and the actual thermalization in an expansion from a class of realistic initial states. The eigenstate thermalization (see [4] and the references therein) – the suppression of the eigenstate-by-eigenstate variance of quantum expectation values of simple observables – provides an ultimate upper bound for a possible deviation of the relaxed value of an observable from its thermodynamical expectation, for any initial state in principle. For the waveguide system the variation of quantum expectation values remains of the order of the mean, even for the energies much larger than any conceivable energy scale of the system. After relaxation from a broad class of initial states, expectation values of observables remain very far from the equilibrium predictions. The thermalization is suppressed even for the infinitely strong interactions between the atoms.

The final state retains some memory of the initial conditions. The deviation of the relaxed expectation value of an observable from the thermal prediction correlates with the initial deviation of it. The ratio of the relaxed and initial deviations is close to the inverse participation ratio. This parameter is a sensitive measure of the approach to a complete chaos. In a quantum chaotic system, a given eigenstate consists of a large superposition of the eigenstates of the underlying integrable system, and the inverse participation ratio is given by the inverse of the number of the principal components of the superposition. The results inspire a more general theory of relaxation in incompletely-chaotic systems with no selection rules [5], of which systems with separable interactions are particular cases. The simple law governing the effect of the loss of memory of the initial conditions is conjectured to cover the whole spectrum of the chaotic behavior—the integrable regime, through the well developed quantum chaos, with the regime of the incomplete chaos in between.

---

[1] V. A. Yurovsky, and M. Olshanii, Phys. Rev. A (in press).
[2] P. Šeba, Phys. Rev. Lett. **64**, 1855 (1990).
[3] Z. Idziaszek and T. Calarco, Phys. Rev. A **71**, 050701(R) (2005).
[4] M. Rigol, V. Dunjko, and M. Olshanii, Nature **452**, 854 (2008).
[5] M. Olshanii and V. Yurovsky, e-print:0911.5587 (2009).

Title: All-optical steering of light via spatial Bloch oscillations in a gas of three-level atoms

Chao Hang[1,2,*] and V. V. Konotop[1,3]

[1]Centro de Física Teórica e Computacional, Universidade de Lisboa, Complexo Interdisciplinar, Avenida Professor Gama Pinto 2, Lisboa 1649-003, Portugal
[2]Department of Physics, East China Normal University, Shanghai 200062, China
[3]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, Edifício C8, Piso 6, Lisboa 1749-016, Portugal
[*]Email: chang@cii.fc.ul.pt

Abstract

Optical beam steering is one of the most important technologies in the modern optics due to its numerous applications. However, the schemes proposed in most of previous studies are restricted to the linear regime. They usually result in a spread of the laser beam because the refractive index gradient of the medium depends on both the optical frequency and the spatial coordinates.

In this work, we propose a scheme where a standing-wave control field applied to a three-level atomic medium in a planar hollow-core photonic crystal waveguide creating periodic variations of linear and nonlinear refractive indexes of the medium. This property can be used for efficient steering of light. We study, both analytically and numerically, the dynamics of probe optical beams in such structures. By properly designing the spatial dependence of the nonlinearity, it is possible to induce long-living Bloch oscillations of spatial gap solitons, thus providing desirable change in direction of the probe beam propagation without inducing appreciable diffraction. Due to the significant enhancement of the nonlinearity, such self-focusing of the probe beam can be reached at extremely weak light intensities.

Ultracold polar molecules in gases and lattices

Paul S. Julienne
Joint Quantum Institute, NIST and the University of Maryland

The availability of sources of cold and ultracold atoms has been extraordinarily fruitful in a wide range of science from precision measurement to novel few-body, many-body and condensed matter systems. In part, this is because the interactions between such atoms can be understood and controlled very precisely. Ultracold molecules, especially polar ones, offer the prospects of extending these successes with new kinds of systems with very different interactions. This talk describes progress towards robust theories of the collisions and reactions of ultracold molecules, emphasizing the value of key simplifying assumptions based of the many orders of magnitude variation in interaction strength during the course of a molecular collision. In particular, when the short range chemical reactivity is high, there is no back-reflection of the reacting species into the long range part of the entrance channel, and molecular collisions exhibit universal elastic and inelastic collision properties that depend only on the long range potential [1]. We have calculated universal collision rates for three-dimensional (3D) cold molecular collisions in gases [2,3] and for quasi-1D or quasi-2D collisions in tightly confining optical lattice structures [4]. Collision rates are analytic for the van der Waals potentials, but need to be calculated numerically for the dipolar potential of interacting polar molecules in an electric field [4,5]. The universal theory is in excellent agreement with experiment for 3D collisions of KRb. The theory predicts that both KRb bosons and fermions can be stabilized by an electric field in sufficiently strong one-dimensional optical lattices with quasi-2D geometry. Lifetimes longer than 1 second, as well as evaporative cooling, should be practical with modest fields and trapping strengths for KRb fermions. While universal species do not have scattering resonances, non-universal species such as RbCs should exhibit scattering resonances when the electric field is tuned. Universal theory should also apply to many nonreactive molecular species in excited vibrational levels.

This work is supported in part by an AFOSR MURI grant A9550-09-1-0617.

[1] P. S. Julienne, Faraday Discuss. 142, 361-388 (2009). (arXiv:0812:1233)
[2] Z. Idziaszek and P. S. Julienne, Phys. Rev. Lett 104, 113202 (2010).
[3] S. Ospelkaus, K.-K. Ni, D. Wang, M. H. G. de Miranda, B. Neyenhuis, G. Quéméner, P. S. Julienne, J. L. Bohn, D. S. Jin and J. Ye, Science 327, 853-857 (2010).
[4] A. Micheli, Z. Idziaszek, G. Pupillo, M. A. Baranov, P. Zoller, and P. S. Julienne, arXiv:1004.5420.
[5] Z. Idziaszek, G. Quéméner, J. Bohn, and P. S. Julienne, unpublished (2010).

Feshbach resonances of harmonically trapped ultracold atoms

Philipp-Immanuel Schneider, Yulian V. Vanne, and Alejandro Saenz
AG Moderne Optik, Institut für Physik, Humboldt-Universität zu Berlin, Newtonstrasse 15, 12489 Berlin, Germany

Confined ultracold atoms with controllable interactions have vast and intriguing applications e.g. for studying new phases of matter, performing quantum information processing, or simulating condensed matter Hamiltonians [1]. The atom-atom interactions are mainly manipulated using a magnetic Feshbach resonance (MFR). The usual theory of MFRs successfully describes the zero-energy limit of the scattering process which is governed by the s-wave scattering length a_{sc}. In traps the particles possess a finite eigenenergy E such that the energy-dependence of a_{sc} is of great importance. This is especially the case for ultracold gases in optical lattices or for confined gases with reduced dimensionality.

We reconsider the scattering process of atoms in a harmonic trap of frequency ω and trap length a_{ho} by applying a two-channel description of an MFR and making use of the analytically known long-range form of the wave function. This allows to derive an equation for the eigenenergies and to quantify the admixture of the resonant molecular bound state (RBS) that leads to the MFR. In order to verify our model we compare it to full multi-channel (MC) calculations and find very good agreement as can be seen in Fig 1.

The eigenenergy equation allows to derive the energy-dependence of the scattering length $a_{\mathrm{sc}}(E)$. One of the main results is that $a_{\mathrm{sc}}(E)$ can differ severely from the energy dependent scattering length derived in free space. This has, e.g., a large impact on the energy spectrum in the trap.

One of the important impacts of the trap on an MFR is a state-dependent magnetic-field shift of the resonance position. Applying the model we were able to quantitatively explain disagreeing positions of the MFR of ^{87}Rb measured in an experiment in a relatively weak dipole trap [2] an in an optical lattice [3].

Another intriguing prediction of our model concerns the RBS admixture to the eigenstates of the system. Considering the open-channel solution in free space the admixture of the RBS has its maximum exactly at the resonance. Thereby effects of the RBS can hardly be distinguished from effects due to a large scattering length. In traps, however, the magnetic-field position of the maximal RBS admixture can be shifted from the resonant magnetic field and in extreme cases can be positioned at vanishing scattering length. This effect is best observable for high lying trap states and for large background scattering length. We considered an experiment by Bourdel *et al.* [4] measuring the atom-loss rate of Fermionic ^{6}Li with a large background scattering length of $-1405\,a_0$ as a function of the magnetic field. The Fermi edge was located at high lying trap levels and our model predicts a correspondingly large shift of $-83.8\,$G of the maximal RBS admixture from the resonance. Exactly in this magnetic field region Bourdel *et al.* observed a *global* maximum of atom loss. This indicates that not the scattering length but the RBS plays a dominant role for atom-loss processes in this system.

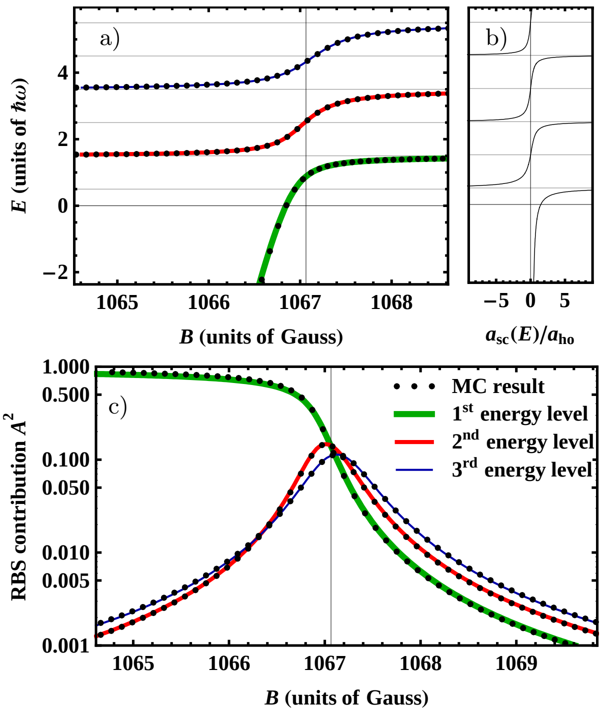

FIG. 1. a) Relative-motion energy spectrum of ^{6}Li-^{87}Rb as a function of the magnetic field B in a trap with frequency $\omega = 2\pi \times 200\,$kHz. Dots indicate MC calculations while lines indicate solutions of the present model. b) Scattering length $a_{\mathrm{sc}}(E)$ corresponding to an eigenenergy E. At $E = \hbar\omega(2n + 1/2)$ with $n = 0, 1, 2, \ldots$ resonances appear. c) Admixture of the RBS (squared) as a function of the magnetic field B.

We acknowledge support of the *Deutsche Forschungsgemeinschaft* and the *Deutsche Telekom Stiftung.*

[1] D. Jaksch and P. Zoller, Annals of Physics, **315**, 52 (2005).
[2] M. Erhard, H. Schmaljohann, J. Kronjäger, K. Bongs, and K. Sengstock, Phys. Rev. A, **69**, 032705 (2004).
[3] A. Widera, O. Mandel, M. Greiner, S. Kreim, T. W. Hänsch, and I. Bloch, Phys. Rev. Lett., **92**, 160406 (2004).
[4] T. Bourdel, J. Cubizolles, L. Khaykovich, K. M. F. Magalhães, S. J. J. M. F. Kokkelmans, G. V. Shlyapnikov, and C. Salomon, Phys. Rev. Lett., **91**, 020402 (2003).

Softening of coherent oscillations and collapse in bosonic Josephson junctions

L. Salasnich[1,2] and G. Mazzarella[1]

[1] *Dipartimento di Fisica "Galileo Galilei", Università di Padova, Via Marzolo 8, 35122 Padova, Italy*

[2] *CNR and CNISM, Research Unit of Padova, Via Marzolo 8, 35122 Padova, Italy*

PACS numbers: 03.75.-b; 03.75.Lm; 05.45.-a

In many experiments atomic Bose-Einstein condensates (BECs) are cigar-shaped due to suitable trapping potentials; these BECs can be separated in two parts by means of an additional axial double-well potential [1]. This kind of geometry is the ideal setup to study the Josephson effect, a macroscopic coherent phenomenon which has been observed in systems as diverse as superconductors [2], superfluid Helium [3] and, recently, also BECs in trapped ultracold atomic gases [4]. The observed coherent dynamics of the atomic BEC in the double-well potential (bosonic Josephson junction) [1, 4] is efficiently described by nonlinear Josephson equations (JEs) [5], which are based on a two-mode approximation of the 1D Gross-Pitaevskii equation (GPE) [6].

In this work we obtain generalized Josephson equations (GJEs) for the fractional imbalance and relative phase of bosonic Josephson junctions by correctly taking into account the dimensional reduction of GPE from 3D to 1D [7, 8], and the effects which are neglected by the familiar Josephson equations of bosonic junctions: the transverse dynamics and the collapse. These GJEs reduce to the familiar JEs in the weak-coupling limit, but show significant qualitative and quantitative differences for strong couplings. In particular, for an attractive BEC (negative inter-atomic scattering length) our GJEs predict the softening of the frequency of the population dynamics both in the Josephson regime and in the self-trapping regime. This frequency reaches a maximum and then goes gradually to zero as the coupling strength approaches the critical value at which there is the collapse of the BEC. We suggest that this novel phenomenon could be observed experimentally by using an ultracold vapor of ^{7}Li atoms by tuning [9] the s-wave scattering length.

[1] O. Morsch and M. Oberthaler, Rev. Mod. Phys. **78**, 179 (2006).

[2] A. Barone and G. Paternò, *Physics and Applications of the Josephson effect* (Wiley, New York, 1982).

[3] O. Avenel and E. Varoquaux, Phys. Rev. Lett. **55**, 2704 (1985); S.V. Pereverzev *et al.*, Nature (London) **388**, 449 (1997); K. Sukhatme *et al.*, *ibid.* **411**, 280 (2001).

[4] F.S. Cataliotti *et al.*, Science **293**, 843 (2001); Y. Shin *et al.*, Phys. Rev. Lett. **92**, 050405 (2004); M. Albiez *et al.*, *ibid.* **95**, 010402 (2005); S. Levy *et al.*, Nature (London) **499**, 579 (2007).

[5] A. Smerzi, S. Fantoni, S. Giovanazzi, and S. R. Shenoy, Phys. Rev. Lett. **79**, 4950 (1997); S. Raghavan, A. Smerzi, S.Fantoni, and S. R. Shenoy, Phys. Rev. A **59**, 620 (1999).

[6] A. J. Leggett, *Quantum Fluids* (Oxford University Press, Oxford) (2006).

[7] L. Salasnich, A. Parola, and L. Reatto, Phys. Rev. A **65**, 043614 (2002); L. Salasnich, A. Parola, and L. Reatto, Phys. Rev. A **70**, 013606 (2004); L. Salasnich and B. A. Malomed, Phys. Rev. A **74**, 053610 (2006).

[8] A. Maluckov, Lj. Hadzievski, B.A. Malomed, L. Salasnich, Phys. Rev. A **78**, 013616 (2008); G. Gligoric, A. Maluckov, L. Salasnich, B. A. Malomed, Lj. Hadzievski, Chaos **10**. 043105 (2009); G. Gligoric, A. Maluckov, Lj. Hadzievski, B.A. Malomed, Phys. Rev. A **79**, 053609 (2009).

[9] K. E. Strecker *et al.* Nature **417**, 150 (2002); L. Khaykovich *et al.*, Science **256**, 1290 (2002); S.L. Cornish *et al.*, Phys. Rev. Lett. **96**, 170401 (2006).

Anderson localization of solitons

Krzysztof Sacha,[1,2] Cord A. Müller,[2,3] Dominique Delande,[2] and Jakub Zakrzewski[1,2]

[1] Instytut Fizyki imienia Mariana Smoluchowskiego and Mark Kac Complex Systems Research Center, Uniwersytet Jagielloński, ulica Reymonta 4, PL-30-059 Kraków, Poland
[2] Laboratoire Kastler-Brossel, UPMC, ENS, CNRS; 4 Place Jussieu, F-75005 Paris, France
[3] Physikalisches Institut, Universität Bayreuth, D-95440 Bayreuth, Germany

At low temperature, a quasi-one-dimensional ensemble of atoms with attractive interaction forms a bright soliton. When exposed to a weak and smooth external potential, the shape of the soliton is hardly modified, but its center-of-mass motion is affected. We show that in a spatially correlated disordered potential, the quantum motion of a bright soliton displays Anderson localization. The localization length can be much larger than the soliton size and could be observed experimentally.

Christoph Zipkes

Department of Physics, Cavendish Laboratory, University of Cambridge,

J J Thomson Avenue, Cambridge CB3 0HE, UK

A trapped single ion inside a Bose-Einstein condensate

In recent years, improved control of the motional and internal quantum states of ultracold neutral atoms and ions has opened intriguing possibilities for quantum simulation and quantum computation. Many-body effects have been explored with hundreds of thousands of quantum-degenerate neutral atoms and coherent light-matter interfaces have been built. Systems of single or a few trapped ions have been used to demonstrate universal quantum computing algorithms and to detect variations of fundamental constants in precision atomic clocks. Now in our experiment we investigate how the two systems can be advantageously combined. We immerse a single trapped Yb+ ion in a Bose-Einstein condensate of Rb atoms[1]. The hybrid setup consists of a linear RF-Paul trap which is overlapped with a magnetic trap and an optical dipole trap for the neutral atoms.

A first synergetic effect is the sympathetic cooling of the trapped ions to very low temperatures through collisions with the ultracold neutral gas and thus without applying laser light to the ions. We observe the dynamics of this effect by measuring the mean ion energy after having an initially hot ion immersed into the condensate for various interaction times, while at the same time monitoring the effects of the collisions on the condensate. The observed ion cooling effect calls for further research into the possibility of using such hybrid systems for the continuous cooling of quantum computers.

To this end a good understanding of the fundamental interaction processes between the ion and the neutrals is essential. We investigate the energy dependant elastic scattering properties by measuring neutral atom losses and temperature increase from an ultracold thermal cloud of Rb. By comparing this with a Monte-Carlo simulation we gain a deeper understanding of how the different parameters affect the collisional effects. Additionally, we observe charge exchange reactions at the single particle level and measure the energy-independent reaction rate constants. The reaction products are identified by in-trap mass spectrometry, revealing the branching ratio between radiative and non-radiative charge exchange processes[2].

Another range of possible applications arises from the high precision with which the ion can be positioned inside the quantum degenerate gas. We demonstrate local probing of the atomic density distribution using a single ion. Combining this with the excellent internal state control we anticipate that this could lead to fundamental studies of the decoherence of a single, locally controlled impurity particle coupled to a quantum environment.

[1]C. Zipkes, S. Palzer, C. Sias, and M. Köhl, Nature 464, 388 (2010).
[2]C. Zipkes, S. Palzer, L. Ratschbacher, C. Sias, and M. Köhl, arXiv:1005.3846

Title: Effects of Ion-Trap Micro Motion on Ultra-Cold Atom-Ion Collisions

Authors: Björn Arnold, Tommaso Calarco, Zbigniew Idziaszek, and Andrea Simoni

Abstract: We investigate collisions of a single RF-trapped ion with a single atom confined in a static trap. For the one- and three-dimensional models we examine the effects of the micro motion induced by the ion trap on the collision dynamics and on the average particle energies. We first perform our calculations employing an idealized description of atom-ion interaction provided through a Fermi pseudo potential. Later we extend to a more general description involving long-range r^{-4} atom-ion interaction supplemented by the quantum-defect boundary conditions at short range. We introduce a new description method for the wave function and the observables by application of a coordinate transformation decoupling the atom-ion interaction from the collision trajectory into a static and dynamic part of the Hamilton operator.

Ion in an ultracold buffer gas

Michał Krych

Instytut Fizyki Teoretycznej, Uniwersytet Warszawski, Hoża 69, 00-681 Warsaw, Poland

We consider controlled collisions between two ultracold atoms guided by external harmonic potentials. We derive analytical solutions of the Schrödinger equation for this system and investigate the properties of eigenergies and eigenstates for different trap geometries as a function of a trap separation and of the scattering length. When varying the trap separation the energy spectrum exhibits avoided crossings, corresponding to trap-induced shape resonances. Introducing an energy-dependent scattering length we investigate the behavior of the system in the vicinity of a magnetic Feshbach resonance. Finally, we illustrate our analytical results with two examples: the quantum phase gate controlled by the external magnetic field and a scheme for a coherent transport of atoms in optical lattices into higher Bloch bands.

Phase spreading of a Bose-Einstein condensate at nonzero temperature

Emilia Witkowska

Instutute of Physics, Polish Academy of Sciences,

Al. Lotników 32/46, 02-668 Warsaw, Poland

I will present our prediction for the evolution of the variance of the Bose-Einstein condensate phase. Using kinetic theory I will show that for a uniform condensate the variance of the phase is growing as $At^2 + Bt + C$ at long times t. The coefficient A vanishes for vanishing energy fluctuations in the initial state while coefficients B and C are insensitive to these fluctuations. B describes diffusive motion of the condensate phase and sets the ultimate limit on the condensate coherence time.

Phase Estimation with Interfering Bose-Condensed Atomic Clouds

Jan Chwedeńczuk

Department of Physics, University of Warsaw, Hoża 69, 00-681 Warsaw, Poland

We investigate how by measuring positions of ultra-cold atoms released from a double-well potential it is possible to estimate a relative phase between the wells. We show that, contrary to what is often assumed, estimation via the fit to the density of the interference pattern gives sensitivity limited by the shot-noise. This bound can be overcome by estimating the phase from the measurement of square root of N (or higher) correlation function. The optimal estimation method requires the measurement of the N-th order correlation function. We also demonstrate, that a simpler estimation method – based on the detection of the center of mass of the interference pattern – gives sub shot-noise sensitivity. Since both these strategies might pose serious difficulties in experimental realization, achievement of sub shot-noise sensitivity with interference pattern seems to be a distant prospect.

Spinor quantum gases: from non-classical states of matter to strongly-correlated gases

Luis Santos

Institut Für Theoretische Physik, University of Hannover,

Appelstraße 2, 30167 Hannover, Germany

In the last years the physics of ultra-cold spinor gases (atoms with spin or pseudo-spin higher than 1/2) has attracted a large interest. In this talk I will first review some of the basic features of ultra-cold spinor gases, and in particular how the interplay between interatomic interactions, Zeeman energy and trapping energy induces a rich physics in these gases, both in what concerns their ground-state phases and the spinor dynamics. I will then present some of our recent results on ultra-cold spinor gases. In particular, I will first discuss parametric amplification of spin-vacuum fluctuations in spinor Bose-Einstein condensates, and the prospects to achieve non-classical states of matter, in particular squeezing. I will then comment on the properties of strongly-correlated fermions in one-dimensional optical lattices. I will specifically show how the quadratic Zeeman effect may induce various types of quantum phase transitions between various magnetic phases of a Mott-insulator of spin-3/2 fermions.

Einstein-de Haas effect in a plaquette-vortex superfluid

Tomasz Świsłocki

Instutute of Physics, Polish Academy of Sciences,

Al. Lotników 32/46, 02-668 Warsaw, Poland

We study a square plaquette of four optical traps containing ultra cold ^{87}Rb atoms in F=1 hyperfine state. In a single axially symmetric harmonic trap the dipolar interactions in a presence of an external resonant magnetic field couple initial $m_F = 1$ component to other Zeeman sublevels. This effect, known as Einsteinde Haas effect in condensed atomic gas, results in effective transfer of atoms to other Zeeman states and leads to a various final states depending on the trap geometry and the value of magnetic fields. We study competition between the local axial symmetry of individual trap and the discrete symmetry of the plaquette. The impact of the global plaquette symmetry on the dynamics can be controlled via the height of the potential barrier separating neighboring traps. In deep axially symmetric micro traps, when tunneling between different traps is suppressed, the local symmetry determines a topology of the final atomic state. Due to the conservation of the zaxis projection of the total angular momentum of interacting atoms a vortex superfluid can be created with vortices localized at individual traps. On the contrary, for shallow traps and larger tunneling the symmetry of the whole plaquette has a dominant influence on the behavior of the system and a discreet single vortex is created.

Vortex Lattices in Anisotropic Traps

N. Lo Gullo[1], S. McEndoo[1], M. Paternostro[2] and Th. Busch[1]

[1]*Department of Physics, University College Cork, Cork, Republic of Ireland*
[2]*School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*

Vortices are topological excitations, which can be observed in rotating, superfluid Bose-Einstein condensates. Due to the single-valuedness condition of the wavefunction they can only carry quantised angular momentum and due to an energetic instability vortices with higher values of angular momentum decay into several vortices with winding number one. These vortices, in turn, arrange themselves into a well ordered lattice structure within the condensate and many beautiful experiments on these structures have been carried out in the recent decade.

Engineering single vortices in these lattices is currently a difficult task as it would require to gain local control over a complex many particle system. Here we present a first step towards this goal, by showing that the structure of the vortex lattice can be changed by taking advantage of phase transitions that occur with increasing anisotropy of the external trapping potential. Each of these spatial re-arrangements can be interpreted in terms of flow patterns in the background gas and is clearly signaled by a change in the behavior of the vortex-lattice eigenmodes.

This new degree of freedom gives a handle to study vortex behaviour and vortex-vortex interactions without being limited to the Abrikosov geometry. In particular the possibility to change to number of nearest-neighbours for a single vortex holds prospects for the use of the vortex winding number in quantum information applications. Furthermore, the topological nature of the vortices makes our findings applicable to systems beyond atomic Bose-Einstein condensates.

Rotonlike instability and pattern formation in non-dipolar Bose-Einstein condensates

Michał Matuszewski

Instutute of Physics, Polish Academy of Sciences,

Al. Lotników 32/46, 02-668 Warsaw, Poland

We show that the excitation spectrum of a metastable phase of an antiferromagnetic spin-1 condensate can exhibit a rotonlike minimum in the absence of long-range dipolar interactions. Under the influence of magnetic field, this minimum gives rise to an instability characterized by wavelengths localized around a nonzero value. By employing numerical simulations within the truncated Wigner approximation, we show that this instability can lead to spontaneous emergence of regular periodic, polygonal, polyhedral or crystalline patterns in the case of sodium condensate confined in a harmonic potential. An explanation of the occurrence of rotonlike instability is given based on the energy and spin conservation laws.

Tunable Molecular Many-Body Physics and the Hyperfine Molecular Hubbard Hamiltonian

Michael L. Wall and Lincoln D. Carr

Department of Physics, Colorado School of Mines, Golden, CO 80401, USA

There has been a great deal of success in recent years using ultracold atoms in optical lattices to explore many-body phenomena, for example to study the dynamics of quantum phase transitions. Now, diatomic molecules are at the edge of quantum degeneracy and offer exciting new prospects for many-body physics. In particular, molecules possess large permanent dipole moments which give rise to a resonant dipole-dipole force which is anisotropic and may be long range. This dipole can couple to external AC microwave fields, giving ready access to tunable dynamics. Molecules also have a rich internal structure of rotational and hyperfine levels which may be dynamically tuned to alter the timescale and number of quantum states involved in many-body dynamics as well as the static many-body properties such as the effective mass. In the pres- ence of strong electric and magnetic fields the rotational and hyperfine degrees of freedom can be independently tuned. In this talk we present an effective low energy lattice Hamiltonian-the Hyperfine Molecular Hubbard Hamiltonian (HMHH)-which describes ultracold molecules in an optical lattice in the pres- ence of strong external fields. These fields are chosen to ensure the stability of the system against dipolar collapse, and so the HMHH represents an experimen- tally natural setting to investigate the novel many-body properties of ultracold molecules. Experimental applications of the Hamiltonian, such as quantum de- phasing, tunable complexity, and the dependence of the phase diagram on the molecular state will be discussed, as well as methods for simulating strongly correlated lattice models in general.

DIPOLAR SPINOR CONDENSATE IN AN OPTICAL LATTICE

Joanna Pietraszewicz

[1] Instytut Fizyki PAN, Aleja Lotnikow 32/46, 02-668 Warsaw, Poland

We study a dipolar spinor condensate of Rb-87 atoms in the F=1 state in an optical lattice. Dipolar interactions couple Wannier states of different angular momentum. The hamiltonian of the system in an external magnetic field for different geometries of the lattice sites is investigated. We show that there exist a number of magnetic resonances. For resonant magnetic fields dipolar coupling of Wannier states with different angular momentum is very strong.

Dipolar resonances in an oscillating magnetic fields

Krzysztof Gawryluk

Wydział Fizyki, Uniwersytet w Białymstoku,

ul. Lipowa 41, 15-424 Białystok, Poland

We consider a spinor condensate of alkali atoms in a $F = 1$ hyperfine state confined in an optical dipole trap. We show the existence of dipolar resonances in the presence of an oscillating magnetic field. Provided the resonance condition is satisfied we find a big transfer of atoms from the $m_F = +1$ state to the $m_F = 0$ one due to the dipole-dipole interactions. This is a realization of a famous Einstein-de Haas effect in system of cold gases. Dipolar resonances make possible to observe this phenomenon even in a very weak dipolar system like condensates of rubidium or sodium atoms.

Oscillating Spinor Solitons

Piotr Szańkowski,[1] Marek Trippenbach,[2] Eryk Infeld,[2] and George Rowlands[3]

[1] *Institute of Theoretical Physics, University of Warsaw, ul. Hoża 69, PL–00–681 Warszawa, Poland*
[2] *Sołtan Institute for Nuclear Studies, ul. Hoża 69, PL-00-681 Warsaw, Poland*
[3] *Department of Physics, University of Warwick, Coventry CV4 7AL, England*

We investigate the properties of three component BEC systems with spin exchange interactions. For special values of coupling constants the system is *Completely Integrable* and supports N-solitons solutions (i.e. singular soliton and the elastic interactions between solitons). We have found that one-soliton solutions can be generalized to the systems with different values of coupling constants, however, they no longer interact with each other elastically. When two generalized solitons collide, a spin component oscillation of the two emerging entities is observed. These entities, we propose to call them the Oscillatons, behave similarly to the solitons. Oscillatons propagate in time without dispersion and retain their character after colliding with each other. A mathematical model is derived for the emerging Oscillatons. Surprisingly, the model is in fact an exact solution to the initial equations and allows for consideration of Oscillatons as a standalone solutions. Generalized solitons are found to be the special case of non-oscillating Oscillatons described be the model.

Exact dynamics and decoherence of two cold bosons in a harmonic trap

Tomasz Sowiński [1,4], *Mirosław Brewczyk* [2], *Mariusz Gajda* [1,5], *Kazimierz Rzążewski* [3,5]

1) Instytut Fizyki PAN, Al. Lotników 32/46, 02-668 Warszawa, Poland
2) Wydział Fizyki, Uniwersytet w Białymstoku, ul. Lipowa 41, 15-424 Białystok, Poland
3) Centrum Fizyki Teoretycznej PAN, Al. Lotników 32/46, 02-668 Warszawa, Poland
4) Wydział Biologii i Nauk o Środowisku UKSW, ul. Wóycickiego 1/3 01-938 Warszawa, Poland
5) Wydział Matematyczno-Przyrodniczy SNS UKSW, Al. Lotników 32/46, 02-668 Warszawa, Poland

We study dynamics of two interacting ultra cold Bose atoms in a harmonic oscillator potential in one spatial dimension. Making use of the exact solution of the eigenvalue problem of a particle in the delta-like potential we study time evolution of initially separable state of two particles. The corresponding time dependent single particle density matrix is obtained and diagonalized and single particle orbitals are found. This allows to study decoherence as well as creation of entanglement during the dynamics. The evolution of the orbital corresponding to the largest eigenvalue is then compared to the evolution according to the Gross-Pitaevskii equation. We show that if initially the center of mass and relative degrees of freedom are entangled then the Gross-Pitaevskii equation fails to reproduce the exact dynamics and entanglement is produced dynamically. We stress that predictions of our study can be verified experimentally in an optical lattice in the low-tunneling limit.