

# Quantum Challenges

September 4–6, 2003  
Falenty near Warsaw, Poland



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## Objectives

The meeting has an interdisciplinary character and aims at defining open problems and the “road map” for the future. Therefore it is focused on the physics of cold particles, which certainly determines the frontiers of the modern atomic, molecular and optical physics.

## Main topics

- ▷ **New trends with cold atoms** (new BEC systems, solitons, cold molecules, fermions, dipolar gases)
- ▷ **Atomic physics meets condensed matter physics** (lattice gases, low dimensional systems, quantum phase transitions, large scattering lengths)
- ▷ **Quantum information with cold atoms and ions** (quantum computing and communications, precision measurements and entanglement)

# Lectures

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# LECTURES

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## **Formation of long-lived ultracold $\text{Li}_2$ molecules**

**Christophe Salomon**

Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris, France

## **Superfluidity of a rotating atomic gas**

**Sandro Stringari**

Università di Trento, Italy

The effects of superfluidity on the rotation of a trapped quantum gas are discussed. At low angular velocity superfluidity shows up in the quenching of the moment of inertia while at high angular velocity it gives rise to vortical configurations, including the formation of vortical lattices. The predictions of rotational hydrodynamics and of sum rules on the collective oscillations (surface oscillations, Tkachenko modes) will be explicitly discussed. Special attention will be devoted to the possibility of observing the effects of superfluidity in ultracold Fermi gases.

**Control of continuum high entanglement  
and the EPR localization limit  
in photon–atom scattering**

**Joseph H. Eberly**

University of Rochester, USA

The dimensionless control parameter for photon–atom entanglement is identified in connection with the EPR localization limit of very high entanglement and very low conditional uncertainty product.

## **Making cold molecules by time-dependent Feshbach resonances**

**Paul S. Julienne, Eite Tiesinga, Thorsten Koehler**

National Institute of Standards and Technology,  
Gaithersburg, Maryland, USA

Making and studying cold molecules is current experimental challenge. If the energy of a tunable Feshbach resonance state is swept in time from above to below the ground state energy of two trapped atoms, then the atoms in a BEC can be converted into diatomic molecular pairs. We give illustrative calculations showing how a simple model, based on the method of Mies, Tiesinga, and Julienne (*Phys. Rev. A* **61**, 022721 (2000)), explains the molecular formation rate. The simple model compares well with full many-body calculations, which also predict a burst of hot atoms in some circumstances. We calculate the molecular physics parameters for the Feshbach resonance near 2 mT for Cs  $F = 3$ ,  $M = 3$  collisions. The predicted molecular formation rate compares well with recent measurements on cold molecule formation in a Cs BEC by the group of R. Grimm at the University of Innsbruck.

## Dynamics of spinor Bose–Einstein condensates

Klaus Sengstock

Institut für Laserphysik, Universität Hamburg, Germany

The investigation of atomic spin systems is central for the understanding of magnetism and a highly active area of research, e.g. with respect to magnetic nanosystems, spintronics and magnetic interactions in high  $T_c$  superconductors. In addition entangled spin systems in atomic quantum gases show intriguing prospects for quantum optics and quantum computation. Bose–Einstein condensates (BEC) of ultra-cold atoms offer new regimes for studies of collective spin phenomena [1–9]. BECs with spin degree of freedom are special in the sense that their order parameter is a vector in contrast to the “common” BEC where it is a scalar. Recent extensive studies have been made in optically trapped Na in the  $F = 1$  state [5–8]. In addition evidence of spin dynamics was demonstrated in optically trapped Rb in the  $F = 1$  state [10]. There is actual interest in extending the systems under investigation to  $F = 2$  spinor condensates which add significant new physics.  $F = 2$  spinor condensates offer richer dynamics, an additional magnetic phase, the so-called cyclic phase [11,12], as well as intrinsic connections to d-wave superconductors.

In the talk first studies of optically trapped Rb  $F = 2$  spinor condensates will be presented. We have measured rates for spin changing collisions for different channels within the  $F = 2$  manifold and we have studied the steady state of the system for various initial conditions. Additionally the thermalization of dynamically populated  $m_F$  condensates will be discussed. Furthermore we present measurements of spin-dependent hyperfine decay rates of the  $F = 2$  state in Rb, as a key to further understanding the intensively studied collisional properties of Rb. As a main result we observe a polar behavior in the  $F = 2$  ground state of Rb, while we measure the  $F = 1$  ground state to be ferromagnetic. Future prospects for the physics with spinor condensates will be discussed.

[1] C.J. Myatt et al., *Phys. Rev. Lett.* **78**, 586 (1997).

[2] D.S. Hall et al., *Phys. Rev. Lett.* **81**, 1539 (1998).

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- [3] M.R. Matthews et al., *Phys. Rev. Lett.* **81**, 243 (1998).
- [4] J.M. McGuirk et al., *Phys. Rev. Lett.* **89**, 090402 (2002).
- [5] J. Stenger et al., *Nature* **396**, 345 (1999).
- [6] H.-J. Miesner et al., *Phys. Rev. Lett.* **82**, 2228 (1999).
- [7] D.M. Stamper-Kurn et al., *Phys. Rev. Lett.* **83**, 661 (1999).
- [8] A.E. Leanhardt et al., *Phys. Rev. Lett.* **90**, 140403 (2003).
- [9] B. Julsgaard, A. Kozhekin, E.S. Polzik, *Nature* **413**, 400 (2001).
- [10] M.D. Barrett, J.A. Sauer, M.S. Chapman, *Phys. Rev. Lett.* **87**, 010404 (2001).
- [11] C.V. Ciobanu, S.-K. Yip, T.-L.Ho, *Phys. Rev. A* **61**, 033607 (2000).
- [12] M. Koashi, M. Ueda, *Phys. Rev. Lett.* **84**, 1066 (2000).

## **Bose-condensates in periodic potentials – some new aspects**

**O. Morsch, M. Cristiani, N. Malossi, M. Iona-Lasinio,  
J.H. Müller, D. Ciampini, E. Arimondo**

INFM, Dipartimento di Fisica, Università di Pisa, Italy

Bose–Einstein condensates in periodic potentials are fast becoming a thriving area of research. In this talk, I shall present some of the recent experiments in this field done in Pisa. In particular, I want to concentrate on non-linear effects due to the mean-field interaction that have interesting consequences for the phase evolution of the condensate as well as the inter-band tunneling behaviour when the periodic potential is accelerated.

**Linearities and nonlinearities:  
photoassociation rates, and the production  
of correlated photons and correlated atoms**

**Paul D. Lett**

Atomic Physics Division, National Institute of Standards  
and Technology, Gaithersburg, Maryland, USA

Photoassociation rates in a Bose–Einstein condensate are linear to far higher intensities than one would expect from classical arguments. While such arguments say that the atoms involved in the photoassociation process must be spaced by approximately the Condon radius for the transition, the photoassociation rate in a Bose–Einstein condensate can be linear in the light intensity even though the mean spacing between the atoms is very much larger than the Condon radius. The rate is linear in intensity and in agreement with two-body scattering theory even where it is predicted that many-body effects may start to play a role.

Correlated photons have been used to test and to explore the limits and peculiarities of quantum mechanics in a number of ways, in particular by testing Bell’s inequalities and by probing experiments based on the well-known suggestions of Einstein, Podolsky and Rosen. While photons are uniquely suited to many of these tests it would also be very interesting to generate correlated beams of atoms, and a number of authors have made proposals to do just that. Many of these proposals involve the dissociation of a molecular Bose–Einstein condensate. Here we propose a method of generating correlated photons and transferring the correlation and/or entanglement of the photons to beams of atoms. Nonlinearities near an atomic resonance in atomic media allow for degenerate four-wave mixing, by which we can produce correlated photons. The advantage of this scheme over the usual parametric down conversion schemes for the generation of correlated photons is that the photons generated are both at the same frequency, and near to an atomic resonance. Time correlation, polarization entanglement, and relative number squeezing are expected. Interacting these photons with an atomic BEC

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can then transfer these correlation and entanglement properties to very slow beams of atoms. Such slow beams could then conceivably be used to perform massive-particle EPR experiments and tests of Bell's inequalities. In particular, delayed-choice experiments would be particularly enabled.

## **Optimal control of Bose–Einstein condensates and degenerate Fermi gases in harmonic traps**

**G.B. McFadden, P.B. Blakie, Charles W. Clark**

National Institute of Standards and Technology,  
Technology Administration, U.S. Department of Commerce,  
Gaithersburg, Maryland, USA

Atomic Bose–Einstein condensates have been produced in a variety of configurations of cold-atom traps. It is desirable to be able to change a trap configuration without exciting the condensate. For example, one may wish to transport a condensate from one place to another by moving the trap, or to change the condensate density by altering the trapping potential, and afterwards have the condensate in the ground state of the new trap configuration, ready for an experiment. It seems obvious that one could always do this by varying the potential sufficiently slowly, so the condensate wavefunction can adjust adiabatically to changing conditions. This talk investigates the possibilities for attaining the desired result without relying on adiabaticity, by programming the time variation of trap parameters so that the condensate is at rest at the end of the process, even though it may be excited at intermediate stages. We demonstrate a simple constructive procedure for programming the time dependence of trap parameters to accomplish this objective.

## What can be learnt from optical fiber solitons?

**Gerd Leuchs**

Institut für Optik, Information und Photonik, Max-Planck  
Forschungsgruppe, Universität Erlangen–Nürnberg, Germany

Solitons appear as dynamically stable wave patterns in several areas of physics. One attractive feature is that a soliton is uniquely described by a single mode function, i.e. a pulse envelope, a center wave length, an amplitude and a phase. Studies of the quantum properties have revealed however, that a soliton has an internal multimode structure [1]. The quantum aspect should be even more significant for BEC solitons because they consist of fewer particles than fiber solitons.

- [1] T. Opatrny, N. Korolkova, G. Leuchs, “Mode structure and photon number correlations in squeezed quantum pulses”, *Phys. Rev. A* **66**, 053813 (2002).

## **Controlling many body states of neutral atoms in optical lattices**

**Olaf Mandel, Markus Greiner, Artur Widera, Tim Rom,  
Theodor W. Hänsch, Immanuel Bloch**

Ludwig-Maximilians-University of Munich  
and Max-Planck-Institut für Quantenoptik, Garching, Germany

When neutral atoms from an atomic Bose–Einstein condensate are loaded into a three dimensional optical lattice potential, one can observe a transition to a Mott insulating regime, where each lattice site is ideally occupied by a single atom. Such a Mott insulator provides a unique environment for quantum information processing, where a qubit is formed by a single atom on a lattice site and a large number of lattice sites of up to  $10^5$  can be filled with atoms.

So far mainly state independent optical lattice potentials have been used to trap Bose–Einstein condensates. However it has been realized that by using spin-dependent potentials one could bring atoms on neighboring lattice sites into contact and thereby realize fundamental quantum gates, excite spin waves, study quantum random walks or realize an almost universal quantum simulator that could be used to study fundamental condensed matter physics Hamiltonians, which are difficult to solve on classical computers. We present our latest results on such controlled collisions between neutral atoms in optical lattices by using spin-dependent optical potentials. In the talk, different signatures of the coherent collisional dynamics of atoms on neighboring lattice sites will be discussed, as well as the possibility to realize a tuneable interstate interaction between atoms on a single lattice site. Extensions of the entanglement scheme will be introduced that incorporate decoherence free subspaces and should allow a large number of repeated quantum gate applications.

We will also discuss recent results on molecule formation in optical lattices via coherent two-photon Raman processes. In these experiments we have been able to achieve a full control over all internal and external quantum mechanical degrees of freedom in a chemical reaction.

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# LECTURES

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## **Atomic quantum dots**

**Peter Zoller**

Institute for Theoretical Physics, University of Innsbruck, Austria

## Dynamics of one-dimensional Bose gases

Luis Santos<sup>1</sup>, Paolo Pedri<sup>1,2</sup>, Patrik Öhberg<sup>1</sup>,  
Sandro Stringari<sup>2</sup>

<sup>1</sup> Institute for Theoretical Physics, University of Hannover, Germany

<sup>2</sup> Università di Trento, Italy

We analyze two different issues related with the physics of one-dimensional Bose gases in the strongly-correlated regime. First, we consider the expansion of a 1D Bose gas, showing that contrary to a 1D Bose–Einstein condensate, the expansion becomes non-selfsimilar when the gas enters the strongly-interacting regime. We also present a variational calculation which allows us to determine the asymptotic properties of the expansion. In the second part, we discuss the physics of coupled 1D Bose gases in an optical lattice. Under appropriate conditions, the gas enters into what we call the quasi-Tonks regime, in which the gas acquires remarkable cross-dimensional properties, since the presence of tunneling allows for a 3D physics, although the chemical potential is that of a 1D gas. We analyze the ground-state properties and low-lying excitation of this sort of systems.

## Dynamics of a Bose–Einstein condensate driven through a Feshbach resonance

**K. Góra**<sup>1,2</sup>, **T. Koehler**<sup>1</sup>, **K. Burnett**<sup>1</sup>

<sup>1</sup> Clarendon Laboratory, Department of Physics, University of Oxford, UK

<sup>2</sup> Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland

Since their first experimental demonstration, magnetic field tunable interactions have been continuously proving their potential and usefulness in the physics of quantum degenerate gases. This technique takes advantage of the Zeeman effect in the electronic energy levels of the atoms to manipulate their binary collision properties in the vicinity of a Feshbach resonance. For several atomic species it is now possible to change the scattering length by orders of magnitude, and even to reverse its sign, making the atoms either repel or attract one another. An impressive application of this technique was the successful creation of stable  $^{85}\text{Rb}$  and Cs Bose–Einstein condensates. These experiments have now been refined to associate pairs of atoms into ultracold molecules and to probe their coherence properties [1]. Binding energies of these highly excited dimer molecules have been measured accurately down to several kHz [1,2]. Very recently, even the direct detection of ultracold molecules, produced via crossing a Feshbach resonance, has been reported by several groups [3].

I will discuss a dynamic microscopic description [4] of the Feshbach-resonance crossing experiments [5] based on the so called cumulant expansion for the correlation functions of the gas [6]. By proper inclusion of the low-energy two-body collisions and a systematic approach to the many-body dynamics in a 3-dimensional trap, we reach full quantitative understanding of the losses observed in the experiments. These losses constitute a serious constraint on the efficiency of molecular production. Our analysis starts with no a priori assumptions on the nature of the states produced and reveals that several conceivable loss mechanisms (including inelastic 3-body processes) can be ruled out in the case considered. A consistent agreement be-

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tween the experimental data and our results identifies the generation of pairs of correlated atoms as the predominant source of condensate loss. We show how to suppress this process. I will also present preliminary results for the many-body shift of the atom-molecule oscillation frequency observed in a recent experiment [2].

The presented theoretical approach can be applied to various situations of experimental interest where losses induced by other types of violent perturbations of the condensate take place. Examples include condensate collisions, four-wave mixing experiments, production of bright solitons or strong external potential driving (e.g. the delta-kicked harmonic oscillator setup).

- [1] E.A. Donley et al., *Nature (London)* **417**, 529 (2002).
- [2] N.R. Claussen et al., *Phys. Rev. A* **67**, 060701 (2003).
- [3] C.A. Regal et al., *Nature* **424**, 47 (2003); S. Dürr et al., cond-mat/0307440; R. Grimm, *Bull. Am. Phys. Soc.* **48**, 111 (2003); J. Cubizolles et al., cond-mat/0308018; S. Jochim et al., cond-mat/0308095.
- [4] T. Koehler, K. Góral, cond-mat/0305060.
- [5] S.L. Cornish et al., *Phys. Rev. Lett.* **85**, 1795 (2000).
- [6] T. Koehler, K. Burnett, *Phys. Rev. A* **65**, 033601 (2002); T. Koehler, T. Gasenzer, K. Burnett, *Phys. Rev. A* **67**, 013601 (2003).

## Ultracold dipolar gases

**Tilman Pfau**

5. Physikalisches Institut, Universität Stuttgart, Germany

In all BECs realized so far, the dominant interaction stems from the isotropic contact potential due to s-wave scattering. Many new interesting features are predicted for a BEC where anisotropic, long-range interactions like the dipole–dipole interaction become important [1]. An ideal candidate for observing effects of the magnetic dipole interaction is atomic chromium with a large magnetic moment of  $6 \mu_B$ .

We present the progress towards a quantum degenerate gas of chromium atoms and report on our recent determination of the sign and the magnitude of the s-wave scattering length of Cr atoms [2] and the investigation of the dipolar relaxation processes in a magnetically trapped chromium gas [3].

- [1] See for example: K. Góral, K. Rzażewski, T. Pfau, *Phys. Rev. A* **61**, 051601 (R) (2000).
- [2] P. Schmidt, S. Hensler, J. Werner, A. Griesmaier, A. Görlitz, T. Pfau, A. Simoni, quant-ph/0303069.
- [3] S. Hensler, J. Werner, A. Griesmaier, P.O. Schmidt, A. Görlitz, T. Pfau, S. Giovanazzi, K. Rzażewski, quant-ph/0307184.

## Molecular BEC and atomic BCS in a cold Fermi gas

Georgy Shlyapnikov

FOM Institute AMOLF, Amsterdam, The Netherlands

I will discuss the formation and behavior of weakly bound bosonic dimers in a cold Fermi gas at a large positive scattering length  $a_{sc}$  for the interspecies interaction. I will present the exact solution for the dimer–dimer elastic scattering and show that these weakly bound dimers exhibit a strong decrease in collisional relaxation with increasing  $a_{sc}$ . The large ratio of the elastic to inelastic rate is promising for achieving Bose–Einstein condensation of the dimers and further cooling the condensed gas. Moreover, adiabatically switching from positive to negative values of  $a_{sc}$ , one may transform the molecular BEC into a highly degenerate Fermi gas, with the ratio of temperature to Fermi energy of the order of 0.01. This suggests a way to achieve a BCS transition in the weakly interacting regime.

## **BEC – the ultimate source of coherent matter waves?**

**Wolfgang Ertmer**

Institute for Quantum Optics, University of Hannover, Germany

Their coherence properties are one of the most fascinating characteristics of Bose–Einstein condensates (BECs). They are essential for the application of BECs as a source of coherent matter waves, i.e. the atom laser, and for the use of BECs in interferometric measurements.

We have studied the phase coherence properties of elongated BECs in detail and observed that the phase of a BEC is not necessarily uniform but undergoes statistical fluctuations. In particular, we observe BECs where the phase coherence length is smaller than the condensate size, i.e. so called quasicondensates.

I will report on our recent interferometric measurement of the coherence length in the regime where strong phase fluctuations are present in our condensates. The method, which is closely related to the stellar interferometer of Hanbury-Brown and Twiss will be discussed and compared to complementary ways of measuring the coherence length.

## **Strongly correlated atoms**

**Keith Burnett**

Clarendon Laboratory, Department of Physics, University of Oxford, UK

I will discuss recent theoretical work on the description of strongly correlated atomic evolution. These correlations are produced when the interactions between atoms become large compared to the kinetic energies available. This can be the case in an optical lattice when the effective kinetic energies are small. If the effective interaction is tuned via a Feshbach resonance, correlation and pairing effects can also be dominant.

I will discuss the theoretical methods needed to describe these systems and the links to condensed matter theory. I will also briefly describe how these strong correlations, i.e. entanglement can be used in precision measurement schemes.

Work supported by the EPSRC, the CQG network, the Royal Society and the Wolfson Foundation.

## Atomic and molecular matter fields in periodic potentials

Klaus Mølmer

QUANTOP – Danish National Research Foundation Center  
for Quantum Optics, Department of Physics and Astronomy,  
University of Aarhus, Denmark

Atoms trapped in moving and in static periodic potentials can be used to experimentally study a number of effects predicted in condensed matter physics: Bloch oscillations, Landau–Zener tunneling, Mott-insulator phase transition, soliton dynamics. Properties and phenomena which have been emphasized in Quantum Optics have also been studied: number and phase squeezing, collapse and revivals of coherence. It has been demonstrated that the interaction of the atoms with the environment and with each other can, indeed, be controlled sufficiently well that coherent behavior can be observed.

In a confining potential, formation of a molecule is a process between discrete states, and one may hope to observe this as a well-controlled coherent process as well [1]. In the talk we shall discuss the prospects of formation of molecules from the atoms in the confined geometry of the periodic potentials. We shall discuss the possibility to form and detect a molecular BEC [2,3], and we shall discuss the use of the association process as a means to generate very non-classical states of atoms and as a diagnostic tool for the state of an atomic field, e.g., of the Mott-insulator transition [4]. If time allows, we shall report on means to fine-tune and control the molecular formation process both in the case of photoassociation and in case of bound state formation in the presence of a Feshbach resonance.

- [1] The loosely bound molecular state formed in the vicinity of an atomic Feshbach resonance indeed displays perfect coherence with the atomic component, cf. the News and Views article by Peter Zoller, *Nature* **417**, 493 (2002).
- [2] B. Damski, L. Santos, E. Tiemann, M. Lewenstein, S. Kotochigova, P. Julienne, P. Zoller, *Phys. Rev. Lett.* **90**, 110401 (2003).
- [3] T. Esslinger, K. Mølmer, *Phys. Rev. Lett.* **90**, 160406 (2003).
- [4] K. Mølmer, *Phys. Rev. Lett.* **90**, 110403 (2003).

## Generation of photon number states on demand

**Herbert Walther**

Sektion Physik der Universität München and Max-Planck-Institut für Quantenoptik, Garching, Germany

In recent years there has been increasing interest in systems capable to generate photon fields containing a preset number of photons. This has chiefly arisen from applications for which single photons are a necessary requirement, such as secure quantum communication and quantum cryptography. Photon number states or Fock states are also useful for generating multiple atom entanglements in strongly coupled systems such as the micromaser. The generated field and the pumping atoms are in an entangled state, this entanglement can be transferred by the field to subsequent atoms, leading to applications such as basic quantum logic gates. For our experiments we employ a micromaser having a cavity  $Q$  of  $4 \cdot 10^{10}$  corresponding to a photon lifetime of 0.3 s which is the largest ever achieved in this type of experiments. A source of single photons or, more generally, arbitrary Fock states is also a useful tool for further investigations of atom-field interaction. It can be used to obtain the reconstruction of purely quantum states of the radiation field as represented by the Fock states.

Recently we succeeded to combine an ion trap with an optical cavity. With this system also single photons in the visible spectral region can be produced on demand.

## **Entanglement in spin and harmonic oscillator lattices**

**F. Verstraete, M. Wolf, M. Popp, J.I. Cirac**

Max-Planck Institute for Quantum Optics, Garching, Germany

We describe certain entanglement properties of multiparticle systems. First, we consider interacting spin systems in a lattice. We will define a new quantity, the localizable entanglement, which measures how much entanglement can be produced between two spins by measuring the rest locally. One can relate this quantity to the two-particle correlation functions, and show how the entanglement length behaves in quantum phase transitions. We have also considered general harmonic oscillator lattices and determined the states and Hamiltonians which give rise to the maximal entangled two-oscillator states.

## **Bloch equations and completely positive maps**

**K. Wódkiewicz**

Institute of Theoretical Physics, Warsaw University, Poland

**S. Daffer, J.K. McIver**

Department of Physics and Astronomy, University of New Mexico, USA

A completely positive map is a transformation of the density operator induced by a unitary quantum reservoir. In this pedagogical presentation, Bloch equations, Kraus operators, and completely positive maps for a qubit will be reviewed. The relation of such maps to the Lindblad equation will be discussed. Examples of such maps with white and colored noise will be presented.

## Entanglement and correlations in higher dimensions

**Jens Peder Dahl**

Chemical Physics, Department of Chemistry, Technical University of Denmark, Lyngby, Denmark

**Wolfgang Schleich**

Abteilung für Quantenphysik, Universität Ulm, Germany

Wave mechanics can create correlations between position and momentum that do not exist in classical mechanics. These correlations appear prominently in s-waves and depend strongly on the number of dimensions of space. They manifest themselves in negative domains of the Wigner function and give rise to shrinking wave packets, or a quadratic dependence of the kinetic energy of the number of particles. Moreover, entanglement of particles is crucial to observe these phenomena. The breakdown of Huygens' principle of electrodynamics in even dimensions is closely related to these phenomena. In particular, it leads to half-integer angular momenta. In this talk we briefly review our work on this topic and relate it to experiments on cold atoms.

- [1] I. Białynicki-Birula et al., *Phys. Rev. Lett.* **89**, 060404 (2002).  
[2] J. Botero et al., *Appl. Phys. B* **76**, 129 (2003).

## **Entanglement of a wave-packet optical mode and a collective atomic-ensemble mode by stimulated Raman scattering**

**Michael Raymer**

Oregon Center for Optics, University of Oregon, Eugene, Oregon, USA

A scheme for creating and characterizing entanglement between a light pulse and an atomic ensemble is proposed. When an atomic ensemble is driven by a short laser pulse transient stimulated Raman scattering (SRS) leads to emission of an intense, near-transform-limited Stokes-shifted light pulse, whose field statistics are similar to those of thermal light [1]. In the absence of collisional dephasing the Stokes field and the atomic ensemble are left in an entangled state. A decomposition of the light and atomic fields into spatial-temporal modes allows the nature of the entanglement to be analyzed in a new way.

When two such atomic ensembles are driven by separate pump laser pulses each creates a Stokes pulse independently, each of which is entangled with its respective atomic ensemble. If these two pulses are interfered on a beam splitter and the energies of the resulting two pulses are measured, the two atomic ensembles are left entangled. This macroscopic entanglement can be read out and characterized by sending second pump pulses into each ensemble and, after superposing the new resulting Stokes pulses on a beam splitter, using homodyne detection to measure the combined quadrature amplitudes.

A new criterion for detecting the presence of entanglement between two (arbitrary) quantum systems is presented [2].

[1] M.G. Raymer, K. Rzażewski, J. Mostowski, *Opt. Lett.* **7**, 71 (1982).

[2] M.G. Raymer, A. Funk, B.C. Sanders, H. de Guise, *Phys. Rev. A* **67**, 052104 (2003).

## Quantum information approach to quantum control: using fractional revivals

Evgeny Shapiro, Michael Spanner, Misha Ivanov

Femtosecond Program, SIMS NRC, Ottawa, Ontario, Canada

This work explores the connection between quantum control of wavepacket dynamics and quantum information processing, borrowing the ideas from quantum computing and bringing them into quantum control.

Firstly, we show how the evolution of a wavepacket created from an initial thermal ensemble can be coherently controlled by manipulating interferences during fractional revivals of the wavepacket.

Secondly, we show how the wavepacket evolution can be mapped onto the dynamics of a few-state system, where the number of states is determined by the amount of information one wants to track about the wavepacket position in the phase space.

Thirdly, taking the information perspective on the dynamics in a multilevel system, we show how fractional revivals allow one to code information into the wavepacket structure. The most peculiar aspect of this perspective is that several qubits can be coded and individually addressed within a single wavepacket excited in a single degree of freedom. Our control scheme is then mapped onto a set of logical gates formally equivalent to standard one-bit and two-bit gates used in quantum computing. Consequently, the number of independent “knobs” or “operations” (such as the number of different laser pulse sequences) required to control wavepacket dynamics in an  $N$ -level system scales with the amount of information carried by the system, i.e. only as  $\log N$ .

Our control approach is illustrated by (i) switching off and on field-free molecular axis alignment induced by a strong laser pulse and (ii) converting alignment into field-free orientation, starting with rotationally cold or hot systems.

## Light–BEC quantum interface

**Eugene S. Polzik**

Niels Bohr Institute, Copenhagen University, QUANTOP – Danish  
National Research Foundation Center for Quantum Optics,  
Copenhagen, Denmark

Our earlier work on squeezed state generation of a thermal atomic sample [1] and entanglement of two thermal gases [2] has been carried out using an interaction of light with optically thick atomic ensembles. Since ultracold atomic samples are characterized by very high densities, combined with long coherence times, such samples are good candidates for light–atoms quantum interface.

Along these lines I will present a recent proposal for generation of a Schrödinger cat state in a multi-atom atomic ensemble [3]. The proposal utilizes an interaction of an ensemble of ultracold atoms in a bad cavity with off-resonant pulses of light, followed by quantum measurements on the light.

Another proposal, in which the quantum interface is achieved by multiple passes of light through an ultracold sample of atoms without any measurements involved will be also briefly discussed [4].

- [1] J. Hald, J.L. Sørensen, C. Schori, E.S. Polzik, *Phys. Rev. Lett.* **83**, 1319 (1999).
- [2] B. Julsgaard, A. Kozhekin, E.S. Polzik, *Nature* **413**, 400 (2001).
- [3] S. Massar, E.S. Polzik, *Phys. Rev. Lett.* **91**, 060401 (2003).
- [4] C. Hemmerich, J.I. Cirac, K. Mølmer, E.S. Polzik, to be submitted.

## **Quantum walks and interfering with the quincunx**

**P.L. Knight, V. Kendon, B. Tregenna**

Blackett Laboratory, Imperial College, London, UK

**B.C. Sanders, S. Bartlett**

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The random walk is interesting both as a concept underpinning diffusive processes as well as a basis for search algorithms in computer science. Galton's quincunx demonstrates the dispersion or spreading characteristic of random walks. Recent work has established that quantization of the random walk, known as the quantum walk, leads to a quadratic enhancement of spreading. We propose a realization of a quantum walk on a circle using a coherent field state in a cavity that undergoes kicks from a two-level atom. The phase of the field spreads quadratically faster than the allowed diffusion rate for classical random walks. This proposed experiment would yield the first realization of a quantum quincunx and may be useful both for enhancing phase diffusion and as an example of a quantum algorithm demonstrating quadratic speed-up.

## Quantum cryptography revisited

**Artur Ekert**

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The theory of computation, including modern cryptography, was laid down almost seventy years ago, was implemented within a decade, became commercial within another decade, and dominated the world's economy half a century later. Quantum information technology is a fundamentally new way of harnessing nature. It is too early to say how important a way this will eventually be, but we can reasonably speculate about its impact on data security. I will review the basic concepts of quantum cryptography and describe both theoretical and experimental techniques which aim to protect information with the ultimate security.



# Posters

## Quantum degenerate Fermi–Bose mixtures

C. Ospelkaus, S. Ospelkaus-Schwarzer, J. Fuchs,  
K. Sengstock, K. Bongs

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Cold dilute quantum gases recently emerged as a near ideal model system reflecting many fascinating phenomena in condensed matter physics. Impressive demonstrations consisted in the experimental observation of vortices, Josephson oscillations and the quantum phase transition from superfluid to a Mott insulator in Bose–Einstein condensates. Fermi systems, in particular stored in optical lattices provide an even more direct link to condensed matter physics and offer a phase diagram at least as rich as the one for Bose systems. The study of atomic Fermi quantum gases has recently led to the observation of quantum degeneracy complemented by first studies on stability and excitations [1–8]. One of the most intriguing aspects of cold Fermi gases is the Pauli exclusion principle resulting in fundamentally different behaviour compared to bosonic systems. Besides the detailed study of excitations in these systems we have a particular interest in fermion correlations influenced by the Pauli principle and possibly changed by the presence of bosons or a BCS transition.

We present progress on the realization of an experimental setup for the simultaneous creation of quantum degenerate samples of fermionic  $^{40}\text{K}$  and bosonic  $^{87}\text{Rb}$ . The apparatus is based on a double MOT design with a 2D source MOT and a 3D collection MOT both acting on both species. After laser cooling, selective forced evaporative cooling of  $^{87}\text{Rb}$  is planned in a magnetic Ioffe–Pritchard trap. The fermionic  $^{40}\text{K}$  component will be sympathetically cooled by the rubidium atoms without additional loss of particles until quantum degeneracy is reached. A high number of fermions is expected by using isotope enriched  $^{40}\text{K}$  dispensers for feeding the 2D source MOT.

We will discuss planned experiments on fundamental excitations such as monopole and quadrupole oscillations, single particle excitations and their influence on heating as well as the possibil-

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ity of observing solitons in Fermi [9] and Fermi-Bose systems. This discussion will be complemented by the presentation of projected experiments on fermion–fermion and fermion–boson correlations in optical lattices, which might also serve as beneficial environment for the observation of a BCS transition.

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## **Deterministic versus spontaneous process in atomic four wave mixing**

**Jan Chwedeńczuk**

Warsaw University, Poland

The widely used Gross–Pitaevski equation treats only coherent aspects of the BEC evolution. However, inevitably some atoms are scattered out of the condensate. We have developed a numerical method based on semi-classical vacuum fluctuations to describe the above mentioned decoherence process. We construct a system composed of a condensate and incoherent bath, with a very weak and random population. These two parts are coupled by four wave mixing processes and a transfer between coherent and incoherent parts occurs. When certain modes in a bath become macroscopically populated, a bosonic stimulation enhances the transition. This process is included in the model. We investigate the role of elastic collisions in the atomic beam splitter and four wave mixing. In the case of two induced de Broglie waves, one seeded wave and one initially empty mode, dynamics can be modeled by simple differential equations. We compare the theory so formulated with numerical results. As a byproduct we can propose an improvement of existing experiments. And enhancement of both the seeded and initially empty mode is possible.

## **Hydrodynamic theory of atomic gases in rotating traps**

**Marco Cozzini, Sandro Stringari**

Università di Trento, Italy

Rotational properties of atomic gases in harmonic traps are discussed, with special emphasis on the collective excitations. Results for the quadrupole modes, both in Bose and Fermi gases, are presented within the framework of hydrodynamic theory. The formation of stripes in a Bose–Einstein condensate containing a vortex array is discussed. The different behaviour of the quadrupole oscillations predicted by the theory of collisional and superfluid hydrodynamics in the presence of rotating traps is proposed as a possible test of superfluidity in Fermi gases.

## **Collisional properties of an ultracold Rb–Cs mixture**

**Matteo Cristiani**

Dipartimento di Fisica, Università di Pisa, Italy

We present the results of an experiment in which we studied the collisional properties of  $^{87}\text{Rb}$  and  $^{133}\text{Cs}$  cooled down to temperatures of a few microkelvin. In particular we measured the elastic cross section for different temperatures.

## Decoherence rates in large scale quantum computers

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Hawthorn, Victoria, Australia

The idealised behaviour of the standard model of a quantum computer involves the features of parallelism, entanglement and unitary evolution of its pure quantum state. The key advantage in comparison with classical computers is that for certain algorithms the number of computational steps needed should increase much more slowly with input number size, enabling previously impossible computations to be carried out [1]. However, the physical system whose quantum states define the  $N$  qubit system and the quantum devices involved in the gating processes both interact with the environment. Such interactions change the density operator describing the quantum computer state from a pure to a mixed state, with coherences between different evolved input states being partially or completely destroyed. This decoherence process degrades idealised quantum computation, though methods such as quantum error correction [2], decoherence free sub-spaces [3] and dynamical suppression of decoherence [4] could be used to minimize its effects. Since quantum computers of practical importance would involve large numbers of qubits (ca  $10^5$  qubits may be needed for searching or factoring algorithms with error correction [5]), the scaling of decoherence rates with the number of qubits is important in determining the size limits of useful quantum computers [6].

This paper extends previous work treating scaling effects [7]. Decoherence effects are studied here for improved models of  $N$  qubit systems (e.g.,  $N$  three level lambda systems trapped in periodic lattices, rather than two level systems), for environments involving both external systems (e.g., EM field modes) and other internal degrees of freedom (e.g., vibrational modes associated with trapped qubit's centre of mass motion). Coherent one and two qubit gating processes are facilitated by a high  $Q$  cavity mode ancilla. Population destroying system-environment interactions are considered. Both the internal

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states of the qubits and their centre of mass position/momentum states are treated. Markovian master equations are used to treat decoherence, assuming that the decoherence time  $t_D$  is large compared to the reservoir correlation time  $t_C$ . Decoherence measures such as the time dependence of the fidelity are used, giving the related decoherence time scales. Situations where independent or collective decoherence occur are examined. Important quantum computer states such as: (a) the Hadamard state; (b) generalised GHZ states are treated.

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## **Shock waves in ultracold atomic gases**

**Bogdan Damski**

Jagiellonian University, Cracow, Poland

We show that an initially broad density perturbation on a Bose–Einstein condensate and ultracold Fermi (Tonks) clouds takes a shock wave form in the course of time evolution. We have developed a simple hydrodynamical approach that allows for analytical calculation of all shock wave properties, e.g. expected position of a shock wave front. Experimental studies of shock waves under assumed theoretical setup seem to be a straightforward task.

## **Study of the pairing transition of the trapped Bose gas with attractive interactions**

**Matthew Davis**

Department of Physics, University of Queensland, St Lucia, Australia

The possibility of a pairing transition in a Bose gas with a partly attractive model interatomic potential was first considered by Evans and Imry in the context of superfluid helium [1]. Neutron scattering experiments indicated that the fraction of Bose condensed particles was small, and it was suggested that the superfluid properties of the system could be due to a different phase transition somewhat analogous to the BCS transition in superconductors, with an order parameter  $m = \langle \psi \psi \rangle$ . Dorre et al. [2] later developed a model that allowed for both condensate and pairing theories and concluded that for helium the condensate theory had the lower free energy and the higher transition temperature.

Later Stoof [3] considered the equation of state for homogeneous alkali gases with an attractive interatomic potential. He found the interesting result that the critical temperature for the pairing transition was higher than that for Bose condensation; however, both these possibilities were preceded by the mechanical collapse of the gas. Jeon et al. [4] recently reached the conclusion that such a system is generally unstable against fluctuations in pairing, and that collapse can occur due to this instability. Mueller and Baym [5] have considered pairing in the trapped gas within the local density approximation, and concluded that the instability towards collapse occurs at lower densities than the pairing instability.

In this paper we use a more sophisticated numerical treatment based on Hartree–Fock Bogoliubov theory to study the possibility of observing the pairing transition in a trapped Bose gas with an attractive delta function interaction. To date calculations in a harmonic trap with a total numbers of atoms smaller than the critical number for collapse have not yielded any significant evidence for pairing.

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However, the parameter space for the problem is quite large, and so recently we have considered the homogenous gas in order to reduce the computational time required. We have imposed physically realistic periodic boundary conditions for the calculation, and this sets a maximum wavelength for fluctuations that stabilizes the gas against the collapse that is expected in the thermodynamic limit. These calculations have suggested that significant pairing can be expected for certain ranges of interaction strength and densities, and the results will be presented in this poster.

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## **Interferometry below the standard quantum limit with Bose–Einstein condensates**

**Jacob Dunningham**

Department of Physics, University of Oxford, UK

Recent experiments that have created Mott insulating (MI) states in optical lattices have provided the BEC community with a very powerful quantum resource. I will discuss some of the exciting possibilities that MI states have for quantum state engineering. In particular, I will focus on how they may be able to be used in practical schemes for achieving interferometry below the standard quantum limit (SQL). To date, schemes for achieving sub-SQL interferometry have shown that the enhancement in phase resolution gained by entangling condensates is lost when dissipation is present or if the effects of finite detector efficiency are considered. These effects make such schemes impractical. I will discuss how it is possible to entangle and disentangle the system in a controlled fashion by passing it through the Mott transition and how this enables us to overcome the destructive effects of dissipation and of imperfect detectors. Such a scheme may enable us to observe the effects of squeezing in a matter wave and may have important practical consequences for high-precision measurements.

## **Condensate heating by atomic losses**

**Jacek Dziarmaga**

Jagiellonian University, Cracow, Poland

Atomic Bose–Einstein condensate is heated by atomic losses. Resulting depletion ranges from 1% in a uniform 3D condensate to 10% in a 1D harmonic trap.

## **Dynamics of spontaneous emission and formation of narrow wave packets of atoms scattered by a standing light wave**

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**V.P. Yakovlev**

Moscow State Engineering Physics Institute, Moscow, Russia

**W.P. Schleich**

Abteilung für Quantenphysik, Universität Ulm, Germany

Atom scattering by a resonant standing light wave is considered. The internal structure of an atom is approximated by a two-level system with a metastable long-living lower level, and with the upper level decaying spontaneously with the rate  $\Gamma$ , predominantly to non-resonant atomic levels. The case of a strong Rabi coupling is studied ( $\Omega \gg \Gamma$ , where  $\Omega$  is the Rabi frequency). This corresponds to the diffraction regime of scattering, in which the initially ideally collimated plane wave splits for a series of many diffraction peaks. The initial atomic momentum is assumed to be perpendicular to the wave vectors of a standing light wave. The problem is solved analytically in the frames of adiabatic and non-adiabatic approximations. In both cases the radiative decay of an atom scattered by a standing light wave is shown to differ significantly from that of an atom in a homogeneous resonant field. The adiabatic regime takes place in a range of medium values of the interaction time  $t$ . In this case the scattering is shown to slow down the radiative decay by giving rise to a non-exponential, power-law behavior of the resonant-level populations. The range of longer times corresponds to the non-adiabatic regime of scattering, in which the power law of a decay turns into the exponential one with a modified rate of decay, which differs significantly from and is much smaller than the field-free width. In parallel to these changes in the decay dynamics, the atomic center-of-mass wave function experiences drastic changes: the initial homogeneous

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plane-wave distribution turns into a series of wave packets localized near anti-nodes of a standing light wave. The widths of wave packets decrease with a growing time (or length) of interaction in the validity range of the power-law decay dynamics and reach their asymptotic time-independent values in the validity range of the non-adiabatic regime of scattering.

## **Atomic Bose–Fermi mixtures in optical lattice**

**Henning Fehrmann**

Institute for Theoretical Physics, University of Hannover, Germany

A mixture of ultra cold bosons and fermions placed in an optical lattice constitutes a novel kind of quantum gas, and leads to phenomena, which so far have been discussed neither in atomic physics, nor in condensed matter physics. We discuss the phase diagram at low temperatures, and in the limit of strong atom–atom interactions, and predict the existence of so far unknown phases that involve pairing of fermions with one or more bosons, or, respectively, bosonic holes. The resulting composite fermions may form, depending on the system parameters, a normal Fermi liquid, a density wave, a superfluid liquid, or an insulator with fermionic domains. We discuss the feasibility for observing such phases in current experiments.

## **Classical field method for Bose–Einstein condensate at finite temperatures**

**Mariusz Gajda<sup>1</sup>, Peter Borowski<sup>2</sup>, Mirosław Brewczyk<sup>3</sup>,  
Kazimierz Rzążewski<sup>2</sup>**

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<sup>2</sup> Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland

<sup>3</sup> University of Białystok, Poland

We study the equilibrium dynamics of a weakly interacting Bose–Einstein condensate confined in a box by using the classical field approximation. We solve the dynamical equations for the classical fields, find the condensate excitations, discuss their spectrum and resulting thermal properties of the system.

## **Dynamical many body theory for molecule association in a Bose–Einstein condensate**

**Thomas Gasenzer**

Institute for Theoretical Physics, University of Heidelberg, Germany

In recent experiments at MIT [1] and JILA [2,3] Feshbach resonances have been exploited to significantly enhance the atomic interactions in a Bose–Einstein condensate and to induce non-trivial coherent dynamics in the many body system. In particular, rapid sweeps across the resonance and special magnetic pulse forms have caused significant loss of condensate atoms which may not be attributed to inelastic and tree-body relaxation processes. At JILA, coherent revival of the condensate fraction has been observed and attributed to the coherent formation of dimer molecules [3].

We present a dynamical mean field theory which allows to describe the phenomena summarized above [4]. The theory represents a significant step beyond the Gross–Pitaevskii and Hartree–Fock approximations in that it enables the description of the mean field dynamics under rapidly changing external conditions. It incorporates explicitly the multi channel structure of the few body scattering processes in the many body sample. The theory allows to compute the many body dynamics for the above experimental configurations and yields insight in the coherent processes which lead to the observed strong losses. For the Ramsey-experiment at JILA [1], we have computed the time evolution of the atomic Rb-85 condensate, of the atoms contributing to the burst, as well as of the fraction of bound dimers, which are shown to form a molecular Bose–Einstein condensate. We discuss the nature of these extremely diffuse, loosely bound molecules and show their emergence in the Feshbach resonant system of open and closed molecular channels. The theory gives a transparent account of the Ramsey-like interference mechanism which leads to the observed oscillations and enables the identification of possible optimization procedures.

More recently we have computed the corresponding time evolution for the sweeps through Feshbach resonances in rubidium and

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sodium, the results of which stress the importance of including the details of the trapping potential. Our theory may be readily extended to describe homonuclear and heteronuclear photoassociative scattering in Bose–Einstein condensates.

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## **Tuning the dipolar interaction in quantum gases**

**Stefano Giovanazzi**

School of Physics and Astronomy, University of St Andrews, UK

We have studied the tunability of the interaction between permanent dipoles in Bose–Einstein condensates. Based on time-dependent control of the anisotropy of the dipolar interaction, we show that even the very weak magnetic dipole coupling in alkali gases can be used to excite collective modes. Furthermore, we discuss how the effective dipolar coupling in a Bose–Einstein condensate can be tuned from positive to negative values and even switched off completely by fast rotation of the orientation of the dipoles.

## Mixtures of bosons and fermions in optical lattices

**Fabrizio Illuminati**

Dipartimento di Fisica, Università di Salerno, Baronissi (SA), Italy

We discuss the physics of mixtures of bosonic and fermionic atoms in periodic potentials at zero temperature. We derive a general Bose–Fermi Hubbard Hamiltonian and study the main qualitative consequences of the model both in homogeneous and trapped geometries [1].

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## **Ground state of two-component degenerate fermionic gases**

**Tomasz Karpiuk<sup>1</sup>, Mirosław Brewczyk<sup>1</sup>,  
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Poland

We analyze the ground state of the two-component gas of trapped ultracold fermionic atoms. We neglect the forces between atoms in the same hyperfine state (the same component). For the case when the forces between distinguishable atoms (i.e., atoms in different hyperfine states) are repulsive, we find the existence of critical interaction strength above which one atomic fraction expels the other from the center of the trap. When atoms from different components attract each other the ground state of the system dramatically changes its structure for strong enough attraction – the Cooper pairs built of atoms in different hyperfine states appear.

## **Two-dimensional vortices in crossed magnetic and electric fields**

**Katarzyna Krajewska**

Institute of Theoretical Physics, Warsaw University, Poland

We analyze a two-dimensional model of electrons moving under the influence of an attractive zero-range potential as well as external magnetic and electric fields. To determine the complex energies of the electron's resonance states the Green's-function method is used. It is found by numerical calculations that there are resonances that have a peculiar dependence on the electric-field intensity, and we show that this phenomenon can be attributed to quantum-mechanical vortices induced by the magnetic field and controlled by the electric-field strength. In order to get more information about these vortices the phase of the wave functions as well as the probability currents for these stable resonances are investigated.

## Coherence properties of guided-atom interferometers

**H. Kreuzmann<sup>1</sup>, U.V. Poulsen<sup>1</sup>, M. Lewenstein<sup>1</sup>,  
R. Dumke<sup>2,3</sup>, W. Ertmer<sup>2</sup>, G. Birkl<sup>2</sup>, A. Sanpera<sup>1</sup>**

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<sup>2</sup> Institute for Quantum Optics, University of Hannover, Germany

<sup>3</sup> Atomic Physics Division, NIST, Gaithersburg, Maryland, USA

We present a detailed investigation of the coherence properties of X-shaped beam splitters and Mach–Zehnder interferometers using guided atoms. The physical parameters are related to those used in [2,3] where two waveguides created by microlenses are used to create the guiding structure. It is demonstrated that such a setup permits coherent wave packet splitting and leads to the appearance of interference fringes. We show that even for thermal input states interference fringes can be clearly observed, since the beam splitter acts analogously to a “color filter”, selecting only a few optimal radial states which contribute to the final signal. Therefore coherence is preserved during the whole process. Finally, we also present improvements by applying optimization strategies.

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## **Spatial period doubling in Bose–Einstein condensates in an optical lattice**

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A standing light wave gives rise to a periodic potential acting on an atom, a so-called optical lattice. Because of interatomic interactions, Bose–Einstein-condensed atoms in such a lattice exhibit a number of unusual features compared with electrons in a crystalline solid. The condensate is generally well described by the Gross–Pitaevskii equation and one finds that for sufficiently strong interactions, “swallow tails” appear in the band structure.

In this work we show that, in addition to states with the usual Bloch form of a plane wave modulated by a function having the same periodicity as the lattice, there exist states with other periods, as well as states which are aperiodic. Using a discrete model appropriate to the tight-binding limit, we derive expressions for the period-doubled states, and investigate the complex logistic map relating the amplitudes of the condensate wave function on neighboring sites. When the amplitudes are chosen to be real, the map is closely related to that for a model used by Bak and Jensen to study structural instabilities in solids. We also give specific examples of period-doubled solutions of the Gross–Pitaevskii equation, and discuss the nature of the energy spectrum.

## **Entanglement preservation in quantum cloning**

**Paweł Masiak**

Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

Recently Galvão and Hardy have shown that quantum cloning can improve the performance of some quantum computation tasks. However such performance enhancement is possible only if quantum correlations survive the cloning process. We investigate preservation of the quantum correlations in the process of non-local cloning of entangled pairs of two-level systems. We consider different kinds of quantum cloning machines and compare their effectiveness in the cloning of non-maximally entangled pure states. A mean entanglement is introduced in order to obtain a quantitative evaluation of an average efficiency for the different cloning machines. We show that a reduction of the quantum correlations is significant and it strongly depends upon the kind of cloning machine used. Losses of the entanglement are largest in the case of the universal quantum cloning machine. Generally, in all cases considered the losses of the entanglement are so drastic that the method of enhancement of performance of the quantum computation using the quantum cloning seems to be questionable.

## **Degenerate quantum gases as a general “physics tool”**

**Patrik Öhberg**

Department of Physics, University of Strathclyde, UK

Degenerate quantum gases can be used to study many different physical phenomena. In this paper we emphasise the analogies between cold atoms and mechanisms which are not directly related to atomic physics. First we study the rapid onset of Bose–Einstein condensation as a way of simulating the dynamics in the early universe where topological defects such as cosmic strings may have been created. Secondly, we show how Landau levels can be created by using light with extremely low group velocity propagating in the quantum gas. This opens up the possibility to study Hall effects in neutral gases.

## **Entanglement in the Bogoliubov vacuum**

**U.V. Poulsen, T. Meyer, M. Lewenstein**

Institute for Theoretical Physics, University of Hannover, Germany

We study the entanglement caused by interactions in a condensate. In particular, we assume a weakly interacting gas in a superfluid state on a lattice. In a quadratic approximation, the ground state is the Bogoliubov vacuum, and we quantitatively investigate the non-local character of this state, applying criteria sensitive to both distillable and so-called bound entanglement.

## **Talbot effect in cylindrical geometry**

**L. Praxmeyer, K. Wódkiewicz**

Institute of Theoretical Physics, Warsaw University, Poland

The Talbot effect is known both in classical optics and in quantum mechanics, but usually the problem of “revival” of an initial state is studied in systems with rectangular symmetry such as infinitely deep well etc. We present how this effect occurs in cylindrical geometry – an example which is quite nontrivial and might be close to applications.

## **Bloch oscillations in Fermi gases**

Mirta Rodriguez

LCE, Helsinki University of Technology, Espoo, Finland

**Päivi Törmä**

Department of Physics, University of Jyväskylä, Finland

The possibility of Bloch oscillations for a degenerate and superfluid Fermi gas of atoms in an optical lattice is considered. For a one-component degenerate gas the oscillations are suppressed for high temperatures and band fillings. For a two-component gas we apply balance equations to describe the effect of collisions on the oscillations. Landau criterion is used for specifying the regime where Bloch oscillations of the superfluid may be observed. We show how the amplitude of Bloch oscillations varies along the BCS–BEC crossover.

## **Images of the dark soliton in a depleted condensate**

**Jacek Dziarmaga, Zbyszek P. Karkuszewski,  
Krzysztof Sacha**

Jagiellonian University, Cracow, Poland

The dark soliton created in a Bose–Einstein condensate becomes grey in course of time evolution because its notch fills up with depleted atoms. This is the result of quantum mechanical calculations which describes output of many experimental repetitions of creation of the stationary soliton, and its time evolution terminated by a destructive density measurement. However, such a description is not suitable to predict the outcome of a single realization of the experiment where two extreme scenarios and many combinations thereof are possible: one will see (1) a displaced dark soliton without any atoms in the notch, but with a randomly displaced position, or (2) a grey soliton with a fixed position, but a random number of atoms filling its notch. In either case the average over many realizations will reproduce the mentioned quantum mechanical result. In this paper we use  $N$ -particle wavefunctions, which follow from the number-conserving Bogoliubov theory, to settle this issue.

## **Entanglement in time-resolved Auger spectroscopy**

**Olga Smirnova, Vladislav Yakovlev, Armin Scrinzi**

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Recently developed XUV light sources with sub-femtosecond pulse durations make it possible to directly observe and control of the dynamics of valence electrons in atoms and molecules. In first experiments XUV pump–laser probe techniques were used to “steer” photoelectron packets by varying pump–probe delay and pulse intensities [1] and to obtain the time-resolved image of an Auger decay [2]. Although the basic physical ideas of the measurements can be phrased in terms of classical mechanics, the observed electron spectra are determined by quantum interference phenomena.

In the present work we unite core-hole formation, Auger decay, and Auger electron streaking by the laser in a consistent quantum theory of time-resolved Auger measurement [2]. The primary purpose of the work is to clarify the role which quantum coherence plays for the final Auger electron spectra. A set of basic equations is derived that is solved numerically. With a few additional approximations we obtain analytical solution, which allows for a clear physical interpretation. The XUV- and Auger electrons turn out to be entangled reflecting the correlation between core-hole formation and Auger decay. We compare quantum results with the predictions of simple model based on the rate equations [2]. In this model the entanglement vanishes. The comparison shows that correlation appears in the spectrum of the Auger electron: for rapid Auger decays electron spectra from quantum theory are broader than in the rate equation model. Indeed, tracing out the final momentum of the XUV-electron leads to the loss of information about the final momentum of Auger electron and this causes spectral broadening. We qualitatively estimate the measure of entanglement using the correlation coefficient introduced in the work [3]. For XUV-time durations much shorter than Auger decay time the entanglement becomes less prominent: quantum and rate equation models give similar Auger spectra. Quantum correlations between the XUV- and Auger electrons can possibly

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be used to increase the time resolution in case of very fast Auger decay.

- [1] R. Kienberger et al., *Science* **297**, 1144 (2002).
- [2] M. Drescher et al., *Nature* **419**, 803 (2002).
- [3] R. Grobe, K. Rzażewski, J.H. Eberly, *J. Phys. B* **27**, L503 (1994).

## **Algebraic approach to the problem of condensation of cavity polaritons**

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**G.P. Miroschnichenko**

Department of Higher Mathematics, St. Petersburg Institute of Fine Mechanics and Optics, St. Petersburg, Russia

**A.V. Rybin**

Department of Physics, University of Jyväskylä, Finland

We consider a problem of Bose condensation of cavity polaritons in semiconductor microcavities containing quantum wells. One of the approaches to describe those polaritons is based on the Dicke model applied to the interaction of the cavity photons with the excitons in a semiconductor. Applying our algebraic approach, developed for various models in quantum optics, we find a spectrum of the Dicke Hamiltonian up to second order with respect to the introduced smallness parameter. The constructed perturbation theory doesn't base on the magnitude of the cavity detuning.

A knowledge of explicit dependence of the spectrum on number of two level particles, which are excitons in our case, allows us to study partition function of a grand canonical ensemble of the system beyond the well-known limit of infinite number of two-level particles. Algebraic reformulation of the Dicke Hamiltonian in terms of so-called dressed operators provides straight forward description of polaritons and their condensation. Coherence properties of the polaritons are studied.

**Is the ground state energy of a Bose condensate  
a function of the scattering length only?**

**Christoph Weiss**

Institut für Physik, Carl von Ossietzky Universität, Oldenburg,  
Germany

It is generally believed that the ground state energy of a translationally invariant Bose condensate is a function of the scattering length only. This topic is reinvestigated both for Bose gases interacting via weak potentials and for Bose gases interacting via (modified) hard core potentials.

## **Pair correlation function of metastable helium condensate**

**Paweł Ziń**

Institute of Experimental Physics, Warsaw University, Poland

The pair correlation function is one of the basic quantities to characterize properties of a Bose–Einstein condensate. We calculate this function in the experimentally important case of a zero temperature Bose–Einstein condensate in a metastable triplet helium state using the variational method with a pair-excitation Ansatz. We compare our result with a pair correlation function obtained for the hard sphere potential with the same scattering length. Both functions are practically indistinguishable above the distance of the scattering length. At smaller distances, due to interatomic interactions, the helium condensate shows strong correlations.

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## **Side event**

To celebrate the 60th birthday of one of the prominent figures of the theoretical AMO physics, **Professor Kazimierz (Kazik) Rzążewski**, a Gala dinner will be given on Saturday, September 6. This is an independent side event and obviously cannot be financed from the public funds, so the participants will have to carry the costs themselves.

	<b>Thursday September 4</b>	<b>Friday September 5</b>	<b>Saturday September 6</b>
	New trends with cold atoms	Atomic physics meets condensed matter physics	Quantum information with cold atoms and ions
9:00– 9:50	<b>Salomon</b> (p. 2)	<b>Bloch</b> (p. 13)	<b>Walther</b> (p. 23)
9:50–10:40	<b>Stringari</b> (p. 3)	<b>Zoller</b> (p. 14)	<b>Cirac</b> (p. 24)
10:40–11:00	coffee	coffee	coffee
11:00–11:30	<b>Eberly</b> (p. 4)	<b>Santos</b> (p. 15)	<b>Wódkiewicz</b> (p. 25)
11:30–12:00	<b>Julienne</b> (p. 5)	<b>Góral</b> (p. 16)	<b>Schleich</b> (p. 26)
12:00–12:30	<b>Sengstock</b> (p. 6)	<b>Pfau</b> (p. 18)	<b>Raymer</b> (p. 27)
12:30–13:00	<b>Morsch</b> (p. 8)	<b>Shlyapnikov</b> (p. 19)	<b>Ivanov</b> (p. 28)
15:00–15:50	<b>Lett</b> (p. 9)	<b>Ertmer</b> (p. 20)	<b>Aspect</b>
15:50–16:10	coffee	coffee	<b>Polzik<sup>a</sup></b> (p. 29)
16:10–16:40	<b>Clark</b> (p. 11)	<b>Burnett</b> (p. 21)	coffee <sup>b</sup>
16:40–17:10	<b>Leuchs</b> (p. 12)	<b>Mølmer</b> (p. 22)	<b>Knight</b> (p. 30)
17:10–17:40			<b>Ekert</b> (p. 31)
19:30–	Poster session		

<sup>a</sup> 15:50–16:20

<sup>b</sup> 16:20–16:40