Specific heat and strong-coupling effects in the BCS-BEC crossover regime of an ultracold Fermi gas

Pieter van Wyk, Hiroyuki Tajima, Ryo Hanai, Yoji Ohashi

1. Department of Physics, Keio University

We theoretically investigate the specific heat in the normal state of an ultracold Fermi gas. Using a strong-coupling BCS-BEC crossover theory, we clarify how strong pairing fluctuations affect this quantity in the whole BCS-BEC crossover region. Recently, the specific heat has been measured in the unitarity limit of this system [1], exhibiting a lambda-like temperature dependence near the superfluid phase transition temperature, as opposed to the well-known T-linear behavior obtained in normal Fermi liquids. We examine whether this anomalous temperature dependence is due to strong pairing fluctuations. We also discuss effects of the so-called pseudogap phenomenon on the specific heat. Since the existence of strong pairing fluctuations is a crucial key in understanding the BCS-BEC crossover physics, our results would be helpful in elucidating their effects on the thermodynamic properties of an ultracold Fermi gas.

References

Perron-Frobenius theorem on the superfluid transition of an ultracold Fermi gas

Naoyuki Sakumichi¹, Norio Kawakami², Masahito Ueda³

1. Theoretical Research Division, Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan
2. Department of Physics, Kyoto University, Sakyo, Kyoto 606-8502, Japan
3. Department of Physics, The University of Tokyo, Hongo, Tokyo 113-0033, Japan

The Perron-Frobenius theorem is applied to identify the superfluid transition of the BCS-Bose-Einstein condensation (BEC) crossover [1]. According to the quantum cluster expansion method of Lee and Yang [2, 3], the grand partition function is expressed by the Lee-Yang graphs. A singularity of an infinite series of ladder-type Lee-Yang graphs [4] is analyzed. We point out that the singularity is governed by the Perron-Frobenius eigenvalue of a certain primitive matrix which is defined in terms of the two-body cluster functions and the Fermi distribution functions. As a consequence, it is found that there exists a unique fugacity at the phase transition point, which implies that there is no fragmentation of BEC of dimers and Cooper pairs at the ladder-approximation level of Lee-Yang graphs. An application to a Bose-Einstein condensate of strongly bounded dimers is also made.

References
Numerical Analysis of Fermion Transport Based on Nonequilibrium Thermo Field Dynamics

Ryosuke Imai, Yusuke Nakamura, Yukiro Kuwahara, Yoshiya Yamanaka

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

We discuss the properties of transport of two-component fermion system. In recent experiments, the nonequilibrium processes of cold atomic gases are observed in detail. Especially for two-component fermion system with a harmonic confinement potential, the dependence of the transport properties on various inter-component interaction strengths were reported [1,2]. In this theoretical study, we analyze the quantum transport equation for the two-component fermion gas in a harmonic potential. To derive the quantum transport equation, we employ Thermo Field Dynamics (TFD), which is a real-time formalism of quantum field theory under thermal situation [3,4]. Because TFD has an advantage in defining an explicit quasiparticle picture even in nonequilibrium situations, it is appropriate to investigate the nonequilibrium process. We compare our numerical results with those of the experiments [1,2] to understand the properties of transport.

References

Triplet pair correlation in a trapped s-wave superfluid Fermi gas at T=0

Yuki Endo¹, Daisuke Inotani², Yoji Ohashi³

1. Department of Physics, Faculty of Science and Technology, Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan

We theoretically investigate effects spatial inhomogeneity of a system on the character of pair correlation in an s-wave superfluid gas of Fermi atoms trapped in a harmonic potential. Within the framework of real-space Boboliubov-de Gennes coupled equations at T=0, we examine to what extent the local breakdown of the spatial inversion symmetry by the harmonic trap potential (except at the trap center) induces the spin-triplet Cooper-pair amplitude in a s-wave superfluid Fermi gas (which is characterized by the ordinary s-wave superfluid order parameter)[1]. We also identify the region where the spin-triplet pair-amplitude is maximally induced in the BCS-BEC crossover region. Since the so-called non-centrosymmetric pairing state has recently attracted much attention in the field of metallic superconductivity, our result would be useful in exploring this novel pairing state in cold Fermi gas system.

References
Diagrammatic Monte Carlo study of the Fermi polaron

Jonas Vlietinck, Jan Ryckebusch, Kris Van Houcke

1. Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, 9000 Gent, Belgium
2. Laboratoire de Physique Statistique, Ecole Normale Supérieure, UPMC, Université Paris Diderot, CNRS, 24 rue Lhomond, 75231 Paris Cedex 5, France

We study the properties of the two-dimensional Fermi polaron model in which an impurity attractively interacts with a Fermi sea of particles in the zero-range limit. We use a diagrammatic Monte Carlo (DiagMC) method which allows us to sample a Feynman diagrammatic series to very high order. The convergence properties of the series and the role of multiple particle-hole excitations are discussed. We study the polaron and molecule energy as a function of the coupling strength, revealing a transition from a polaron to a molecule in the ground state. For all considered interaction strengths, the polaron $Z$ factor from the full diagrammatic series almost coincides with the one-particle-hole result. We also formally link the DiagMC and the variational approaches for the polaron problem at hand.

References
Strongly dipolar Fermi gases of erbium atoms

Kiyotaka Aikawa\textsuperscript{1}, Simon Baier\textsuperscript{1}, Albert Frisch\textsuperscript{1}, Michael Mark\textsuperscript{1}, Cornelis Ravensbergen\textsuperscript{1, 2}, Rudolf Grimm\textsuperscript{1, 2}, Francesca Ferlaino\textsuperscript{1}

1. Institut für Experimentalphysik and Zentrum für Quantenphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
2. Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria

We report on the observation of few- and many-body dipolar phenomena in a quantum degenerate Fermi gas of strongly magnetic erbium atoms. We demonstrate a new evaporative cooling scheme where spin-polarized fermions are directly cooled down to 0.1 times the Fermi temperature via universal dipolar scattering [1]. In cross-dimensional rethermalization measurements, where the sample is driven out of equilibrium, we reveal the anisotropic character of the interaction and observe that the system relaxes to equilibrium with speeds that strongly depend on the dipole orientation [2]. Furthermore, we show that the Fermi surface of our sample is deformed to an ellipsoid by the many-body DDI and that the magnitude of the deformation is tunable via an external trapping potential. The observed Fermi surface deformation represents a crucial step for exploring exotic quantum nematic phases in the ultracold regime [3].

References
Quantum Monte Carlo simulations of multicomponent Fermi systems

Masaru Sakaida, Norio Kawakami

1. Department of Physics, Kyoto University, Kyoto 606-8502, Japan

In cold atomic systems, several species of atoms have multiple low-lying hyperfine states. By loading these atoms into optical lattices, we can realize the multicomponent Fermi systems. Recently, six-component Fermi systems were experimentally realized[1], and have attracted much interest.

These backgrounds motivate us to study quantum condensed phases and quantum phase transitions which can be observed in attractively interacting multicomponent Fermi systems. For this purpose, we apply the Quantum Monte Carlo scheme[2] to the multicomponent Hubbard model with attractive interaction, and calculate the pair-correlation function and the charge-correlation function. In this poster presentation, we will show the results of these two functions and discuss how the fluctuations of pair-correlation and charge-correlation lead to the pseudo-gap formation.

References

Decoherence of many fermions in an optical lattice due to spontaneous emissions

Saubhik Sarkar¹, Stephan Langer¹, Johannes Schachenmayer², Andrew Daley¹, ³

1. Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
2. JILA, NIST, Department of Physics, University of Colorado, 440 UCB, Boulder, CO 80309, USA
3. Department of Physics and SUPA, University of Strathclyde, Glasgow G4 0NG, Scotland, U.K.

A key experimental challenge in reaching low-entropy states with ultra cold fermionic atoms in optical lattices arises from various heating and decoherence mechanisms. We investigate how many-body states are affected by spontaneous emission processes at a rate that can be comparable to the typical dynamical timescales in systems of two-component fermions. Deriving a many-body master equation, we show that magnetic order for strong repulsive interactions can be robust against this decoherence mechanism, in a way that also generalizes to group-II species exhibiting SU(N) magnetism. For attractive interactions, decay rates are faster, and are enhanced by superradiance. We also consider effects of lattice atoms immersed in a Bose-Einstein condensate, analysing changes in properties of lattice atoms due to this entanglement with the condensate for various interaction strengths.

BOSE GASES
Faraday waves in collisionally inhomogeneous multi-component Bose-Einstein condensates

Antun Balaž¹, Alexandru Nicolin²

1. Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia
2. Department of Computational Physics and Information Technologies, Horia Hulubei National Institute of Physics and Nuclear Engineering, P. O. Box MG-6, 077125, Romania

Faraday (density) waves in Bose-Einstein condensates (BECs) can be excited by harmonic modulation of the interaction or the trapping potential. We will study the emergence of Faraday waves in binary non-miscible BECs [1]. We will show that the excited waves are of similar periods, emerge simultaneously, and do not impact the dynamics of the bulk. We will derive analytically their spatial periods and analyze the behavior of the system driven at resonant frequencies, which turns the two components miscible.

We will also investigate Faraday waves in multi-component BECs with spatially inhomogeneous interactions [2]. In the regime of weak inhomogeneity, we will show that the properties of generated waves are similar to the homogeneous case, while in the strong inhomogeneity regime the periods of density waves strongly depend on the typical length scale of the inhomogeneity. We will derive variational theory for spatial periods of density waves for both cases.

References
Stochastic Coupled Growth of 2-Component Bose-Einstein Condensates

Nick Proukakis¹, I-Kang (Gary) Liu², Rob Pattinson¹, Simon Gardiner⁴, Simon Cornish⁴, Nick Parker¹, Shih-Chuan Gou²

¹. Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics & Statistics, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
². Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
³. Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University, Durham, DH1 3LE, UK

We investigate [1] the competing growth dynamics of highly immiscible two-component condensates |1>, |2> under realistic experimental conditions (partly motivated by the Durham Rb-Cs mixture experiment [2, 3]). Our modelling is performed via fully three-dimensional coupled stochastic projected Gross-Pitaevskii equations, with dynamics induced by sudden temperature and chemical potential quenches. In brief, we typically find one of the two components (|1>, Rb) to condense faster than the other (|2>, Cs), which is sympathetically cooled, in agreement with experimental observations. The condensing component |1> exhibits spontaneous appearance of one, or more, dark solitons [via the Kibble-Zurek mechanism], with component |2> gradually condensing in phase-separated regions of low mean-field potential, so either within the dark soliton(s), or around the edges of the emerging condensate in component |1>. The ensuing dynamics can lead to a very rich structure, with observations of emerging immiscible profiles over experimental timescales depending sensitively on the extent to which the stochastically-generated dark soliton(s) in |1> fill in by condensing |2> atoms (thus leading to spontaneously-generated dark-bright soliton(s)) before the dark soliton(s) themselves decay stochastically [4].

We acknowledge financial support from the EPSRC (grant nos. EP/K03250X/1, EP/K030558/1) and the NSC Taiwan.

References
**Creation of Topological Monopole Defects In a Quantum Field**

Konstantin Tiurev¹, Emmi Ruokokoski¹, Mikko Möttönen¹,², Michael Ray³, David Hall³

1. QCD Labs, COMP Centre of Excellence, Department of Applied Physics, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland
2. Olli V. Lounasmaa Laboratory, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland
3. Department of Physics, Amherst College, Amherst, Massachusetts 01002-5000, USA

Among all types of topological defects, point defects play an especially important role because they correspond to stable elementary particles in grand unified gauge theories. Lack of experimental evidence of monopoles in real electromagnetic fields has striven the search for monopole analogues in other systems. In our studies we use dilute alkali Bose-Einstein condensates (BEC) as a platform to observe topological point defects. These systems are interacting quantum gases amenable to theoretical analysis, and thus provide unique possibilities for testing the fundamental principles and theories of many-particle quantum physics. Recently, we demonstrated a method to create Dirac monopoles in a synthetic magnetic field of BEC [1,2]. In our current studies, the method is modified to observe topological point defects reminiscent to those predicted theoretically by 't Hooft and Polyakov as quantized magnetic charges. The experiments show excellent quantitative agreement with simulations without any free parameters.

References

**Observation of Dirac monopoles in a synthetic magnetic field**

M. W. Ray¹, E. Ruokokoski², S. Kandel¹, M. Möttönen²,³, D. S. Hall¹

1. Department of Physics, Amherst College, Amherst, Massachusetts 01002-5000, USA
2. QCD Labs, COMP Centre of Excellence, Department of Applied Physics, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland
3. Olli V. Lounasmaa Laboratory, Aalto University, P.O. Box 13500, FI-00076 Aalto, Finland

The spin degree of freedom of an atomic Bose-Einstein condensate (BEC) generates synthetic electromagnetic fields that can be manipulated by real time-varying magnetic fields. We present the experimental creation and observation of Dirac monopoles in the synthetic magnetic field of a ⁸⁷Rb BEC [1]. This constitutes the first time Dirac monopoles are observed in a system governed by a quantum field. The experiments are accurately simulated using a mean-field approach, and a very good quantitative agreement is obtained without any fitting parameters.

References
Spin-nematic order and phase locking in antiferromagnetic spinor condensates

Camille Frapolli\textsuperscript{1}, Vincent Corre\textsuperscript{1}, Tilman Zibold\textsuperscript{1}, Lingxuan Shao\textsuperscript{1}, Jean Dalibard\textsuperscript{1}, Fabrice Gerbier\textsuperscript{1}

1. Laboratoire Kastler Brossel, Ecole Normale Supérieure, Collège de France, UPMC, CNRS, 11 Place Marcelin Berthelot, 75005 Paris

We study the equilibrium state of a spin-1 Bose-Einstein condensate of sodium with antiferromagnetic interactions. The equilibrium populations in the mean field ground state are determined by the competition between the antiferromagnetic interactions that tend to minimize the total spin of the system, and the quadratic Zeeman effect which favors atoms in the $m_F = 0$ state. In order to minimize the magnitude of the transverse spin, antiferromagnetic interactions lock the relative phase $\Theta = \Phi_+ + \Phi_- - 2\Phi_0$ to $\pi$. By applying a spin rotation along the transverse direction, we map the transverse spin fluctuations to the variance of $S_z$ and measure them directly. We verify the phase locking due to antiferromagnetic interactions at several points on the phase diagram of the system.

Quantum fluctuation of soliton in Bose-Einstein condensate beyond Bogoliubov approximation

Junichi Takahashi\textsuperscript{1}, Yusuke Nakamura\textsuperscript{1}, Yoshiya Yamanaka\textsuperscript{1}

1. Department of Electronic and Photonic Systems, Waseda University, Tokyo 169-8555, Japan

The system of Bose-Einstein condensate (BEC) has a zero mode associated with the spontaneous breakdown of the global phase symmetry. However, the treatment of the zero mode is difficult because of its singular property, and has often been neglected. To remove this singularity, we have recently proposed the new treatment of the zero mode, and been able to introduce a ground state of the zero mode [1]. Using this ground state, we have evaluated the quantum fluctuation for the phase of BEC. When a dark soliton exists in BEC, an additional zero mode which is associated with translational symmetry appears. It is well known that this zero mode contributes to the fluctuation of position and momentum of the soliton [2]. Using the method of Ref. [1], we evaluate the quantum fluctuations of position and momentum and compare with the result of Ref. [2].

References

Classical and quantum reflection of bright matter-wave solitons

Anna Marchant\textsuperscript{1}, Thomas Billam\textsuperscript{2}, Manfred Yu\textsuperscript{1}, Simon Gardiner\textsuperscript{1}, Simon Cornish\textsuperscript{1}

1. Joint Quantum Centre (JQC), Durham—Newcastle, Department of Physics, Durham University, Durham DH1 3LE, UK
2. Jack Dodd Centre for Quantum Technology, Department of Physics, University of Otago, Dunedin 9016, New Zealand

Bright solitons are non-dispersive wave solutions, arising in a diverse range of nonlinear, one-dimensional (1D) systems, including atomic Bose-Einstein condensates with attractive interactions.

We report the controlled formation of a bright solitary matter-wave \cite{Marchant1} from a Bose-Einstein condensate of \textsuperscript{85}Rb \cite{Marchant2}. We demonstrate the reflection of the solitary wave from a broad repulsive Gaussian barrier and contrast this to the case of a repulsive condensate, in both cases finding excellent agreement with theoretical simulations using the 3D Gross-Pitaevskii equation. For an attractive potential we identify a regime where quantum reflection of the solitary wave is possible.

These results pave the way for new experimental studies of bright solitary matter-wave dynamics to elucidate the wealth of existing theoretical work and to explore an array of potential applications including novel interferometric devices, the realisation of Schrödinger cat states and the study of short-range atom-surface potentials \cite{Cornish}.

References

Bright solitons in quasi-one-dimensional dipolar condensates with spatially modulated interactions

Fatkhulla Abdullaev1, Arnaldo Gammal2, Boris Malomed3, Lauro Tomio1, 4

1. Instituto de Física Teórica, Universidade Estadual Paulista, 01140-070, São Paulo, São Paulo, Brazil
2. Instituto de Física, Universidade de São Paulo, 05508-090, São Paulo, São Paulo, Brazil
3. Department of Physical Electronics, School of Electrical Engineering, Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel
4. Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, 09210-170, Santo André, Brazil

We introduce a model for the condensate of dipolar atoms or molecules, in which the dipole-dipole interaction (DDI) is periodically modulated in space due to a periodic change of the local orientation of the permanent dipoles, imposed by the corresponding structure of an external field (the necessary field can be created, in particular, by means of magnetic lattices, which are available to the experiment). The system represents a realization of a nonlocal nonlinear lattice, which has a potential to support various spatial modes. By means of numerical methods and variational approximation (VA), we construct bright one-dimensional solitons in this system and study their stability. In most cases, the VA provides good accuracy and correctly predicts the stability by means of the Vakhitov-Kolokolov criterion. It is found that the periodic modulation may destroy some solitons, which exist in the usual setting with unmodulated DDI and can create stable solitons in other cases, not verified in the absence of modulations. Unstable solitons typically transform into persistent localized breathers. The solitons are often mobile, with inelastic collisions between them leading to oscillating localized modes.

References

Modeling Bose-Einstein Condensates in Non-Uniformly Rotating Reference Frames

Martin Kandes1, 2

1. Computational Science Research Center, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182
2. Institute of Mathematical Sciences, Claremont Graduate University, 150 E. 10th St., Claremont, CA 91711

We present the implementation of a method-of-lines approach for numerically approximating solutions of the time-dependent Gross-Pitaevskii equation in non-uniformly rotating reference frames. Implemented in parallel using a hybrid MPI + OpenMP framework, which will allow for scalable, high-resolution numerical simulations, we utilize an explicit, generalized 4th-order Runge-Kutta time-integration scheme with 2nd- and 4th-order central differences to used approximate the spatial derivatives in the equation. The principal objective of this project is to model the effect(s) of rotationally-induced perturbations on quantized vortices within weakly-interacting dilute atomic gas Bose-Einstein condensates in the mean-field limit of the Gross-Pitaevskii equation. Here, we discuss our work-to-date and preliminary results.
**Persistent Non-Equilibrium States In Perfectly Spherical Potentials**

Dan Lobser$^1$, Andrew Barentine$^1$, Heather Lewandowski$^1$, Eric Cornell$^1$

1. JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder

Using his transport equation, Boltzmann found that the monopole mode of a gas in an isotropic harmonic potential is undamped [1,2]. This elegant many-body dynamical symmetry has never been observed because of the difficulty in realizing a perfectly isotropic harmonic trap. Through a modification to the standard TOP trap, we gain full control over the ellipsoidal parameters of the 3D potential allowing us to achieve spherical symmetry at a level of 0.1%. Damping rates are measured in the presence of controlled symmetry breaking and are explained in the context of monopole/quadrupole mixing.

**References**


**Dynamics of Breather in linearly coupled Bose-Einstein Condensates**

Shih-Wei Su$^1$, Shih-Chuan Gou$^1$, I-Kang Liu$^1$, Ashton Bradley$^2$, Oleksandr Fialko$^3$, Joachim Brand$^3$

1. Department of Physics and Graduate Institute of Photonics, National Changhua University of Education, Changhua 50058 Taiwan
2. Jack Dodd Centre for Quantum Technology, Department of Physics, University of Otago, Dunedin, New Zealand
3. Centre for Theoretical Chemistry and Physics, New Zealand Institute for Advanced Study, Massey University (Albany Campus), Auckland, New Zealand

The emergent sine-Gordon dynamics [1] in weakly coupled Bose-Einstein condensates (BECs) has been actively studied in recent years. An interesting property of sine-Gordon equation is that it possesses a class of solitonic solution [2], called breather, which is a spatially-localized and temporarily-oscillating nonlinear wave. In this presentation, we investigate the evolution of a phase-imprinted sine-Gordon breather in the relative phase of two coupled 1D BECs by numerically integrating the coupled Gross-Pitaevskii equations. We find that, in the weak-coupling regime, the breather-like excitation occur in both the relative and total phases when the initial amplitude of the breather is sufficiently small, otherwise the imprinted breather would decay into two dark solitons instantly. The stability of the breather is examined by varying the frequency of the imprinted breather and the coupling energy between the condensates.

**References**

Scissors mode and quantized vortices generated in sodium Bose-Einstein condensates by a rapid modulation of the magnetic field

Masahiro Yamazaki$^1$, Miho Harada$^1$, Atsuo Morinaga$^1$

$^1$. Tokyo University of Science

When the magnetic field strength at the center of a cloverleaf trap for sodium Bose-Einstein condensates in a few milliseconds using an additional off-axis Helmholtz coil, the center-of-mass oscillation in the radial direction, the $m=0$ low-lying and high-lying quadrupole modes, and the scissors mode were excited simultaneously in the condensates. The amplitude of the scissors mode was modulated by the frequency of the $m=0$ low-lying quadrupole mode due to the law of conservation of angular momentum. On the other hand, the sign of the potential was reversed with a reverse time of 11.7 ms through zero, and the potential was hold during 1 ms and returned back rapidly. Thus, the condensates in the $m=0$ state with a clear quantized vortices was extracted from the condensates in the $m = -1$ state by the Majorana transition.

Position-dependent spin-orbit coupling for ultracold atoms

Gediminas Juzeliūnas$^1$, Artūnas Acus$^1$, Julius Ruseckas$^1$, Ian Spielman$^2$, Luis Santos$^3$, Shih-Wei Su$^4$, Shih-Chuan Gou$^5$

$^1$. Institute of Theoretical Physics and Astronomy, Vilnius University, A. Goštauto 12, LT-01108 Vilnius, Lithuania
$^2$. Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, Gaithersburg, Maryland, 20899, USA
$^3$. Institut für Theoretische Physik, Leibniz Universität, Hannover, Appelstrasse 2, D-30167, Hannover, Germany
$^4$. Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan

Recently several schemes have been proposed to create the spin-orbit coupling (SOC) of the Rashba-Dresselhaus type for ultracold atoms by illuminating them with several laser beams [1,2]. This leads to a number of distinct phenomena, such as formation of non-conventional Bose-Einstein condensates (BECs) of ultracold atoms affected by the SOC [2,3]. Here we explore effects due to the position-dependence of the SOC for atomic BECs. The position-dependence provides domains of the stripe phases with the stripes oriented in different directions. It is shown that non-trivial structures can be formed at the boundaries of these domains, such as defects or arrays of vortices and anti-vortices.

References

Toward simulating artificial gauge fields with atom-chip based quantum simulator

Seiji Sugawa1, Abigail Perry1, Francisco Salces-Carcoba1, Ian Spielman1

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

Quantum degenerate gases are well suited for studying quantum many-body phenomena, both as quantum simulators and also as novel physics systems of their own right. Experimental realizations of artificial gauge fields implemented with Raman-dressed alkali atoms have open-up the possibilities of exploring topological quantum matter with cold atoms. However, one inevitable issue with such scheme is heating effect due to photon-scattering from the Raman lasers, which may hinder future observation of intriguing topological phenomena. We are developing an alternative scheme using RF-dressed states that realize the same kind of Hamiltonian, but have essentially no heating. This scheme works for any alkali atom (boson or fermion) uses an array of ac-current carrying wires on a nanofabricated atom chip to create effective Raman coupling for atoms trapped near the chip surface [1]. We will show the experimental feasibility and report on the progress toward the implementation using rubidium atoms.

References
Roton and phonon modes softening in quantum gases with spin-orbit coupling

Si-cong Ji\textsuperscript{1}, Long Zhang\textsuperscript{1}, Xiao-tian Xu\textsuperscript{1}, Zhan Wu\textsuperscript{1}, Youjin Deng\textsuperscript{1}, Shuai Chen\textsuperscript{1}, Jian-Wei Pan\textsuperscript{1}

1. Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China

Roton-type excitations emerge from strong or long-range interactions in conventional superfluids. Here we demonstrate a new route to induce roton modes by manipulating the single-particle Hamiltonian in weakly short-range interacting quantum gases. Using Bragg spectroscopy, we measure the excitation spectrum of a spin-orbit coupled Bose-Einstein condensate in the magnetized phase, which possesses a typical phonon-maxon-roton structure in the spin-orbit coupling direction. It is observed that the roton or phonon mode softens as the condensate is tuned to undergo a relevant quantum phase transition. In addition, the validity of the \( f \)-sum rule in this system is verified. This work blazes a trail for quantum simulation of strong-correlation physics.

References

Experimental apparatus for producing the Bose-Einstein condensate of Ytterbium(Yb)

Jongchul Mun, Jeongwon Lee, Jae Hoon Lee, Jiho Noh

1. Korea Research Institute of Standards and Science (KRISS)

We report our experimental apparatus for producing ultracold Yb isotopes. The experimental setup consists of three parts: 1. oven and Zeeman slower, 2. main magneto-optical trap chamber, 3. auxiliary science chamber. The oven is designed to have a cold finger inside in order to avoid the nozzle clogging issue, and the Zeeman slower magnetic field profile is set to cross the zero. For magneto-optical trap, two different wavelength lasers (399nm & 556nm) are used to increase the capture velocity and trapped atom number. The detailed design of our setup and the performance of our Zeeman slower and magneto-optical trap would be presented.
Numerical analysis of quantum transport equation derived from nonequilibrium Thermo Field Dynamics in Markovian approximation

Yukiro Kuwahara¹, Yusuke Nakamura¹, Ryosuke Imai¹, Yoshiya Yamanaka¹

¹. Department of Electronic and Photonic Systems, Waseda University, Tokyo, Japan

We study the quantum transport equation derived from nonequilibrium Thermo Field Dynamics (TFD) [1] in the system of cold neutral atomic Bose gas. In our previous works [2], [3], we have applied nonequilibrium TFD to the system with a time-dependent external field. Imposing the renormalization conditions on the improved time-dependent on-shell self-energy, we derived the non-Markovian quantum transport equation and obtained the corrections of the quasiparticle energy. The energy corrections have the off-diagonal hermitian and the imaginary parts, which play crucial roles in the thermal process [2], [3].

Since the cost of numerical calculation of the non-Markovian transport equation is extremely high, we consider it in the Markovian approximation. First, we compare the numerical results of the non-Markovian and the Markovian transport equations for small systems. Then we analyze thermal processes for larger systems, calculating the Markovian transport equation numerically.

References

Experimental probing of non-equilibrium Quantum Many-Body Systems

Thomas Schweigler¹, Bernhard Rauer¹, Maximilian Kuhnert¹, Remi Geiger¹, Tim Langen¹, Jörg Schmiedmayer¹

¹. Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria

The study of the non-equilibrium dynamics of isolated quantum many-body systems is a highly active research topic with relevance for many different fields of physics. Despite important theoretical effort, no generic framework exists yet to understand when and how a quantum system relaxes to a steady state.

Over the last years we have developed techniques to experimentally investigate this question. In our experiments we study degenerate 1d Bose gases which are brought out of equilibrium by various types of quantum quenches. The interference of two such gases results in a fluctuating matterwave interference pattern. The noise and correlations in such interference patterns open a probe into the many-body states of the 1d Bose gas, its fluctuations and relaxation. With this method we observe light-cone-like correlation dynamics, thermal-like steady states and the appearance of a unified statistical description for quantum many-body systems.
Creation of excitations from a uniform impurity motion in the condensate

Jun Suzuki

1. Graduate School of Information Systems, The University of Electro-Communications, Tokyo, Japan

We investigate a phenomenon of creation of excitations in the homogeneous Bose–Einstein condensate due to an impurity moving with a constant velocity. A simple model is considered to take into account dynamical effects due to motions of the impurity. Based on this model, we show that there can be a finite amount of excitations created even if velocity of the impurity is below Landau’s critical velocity. We also show that the total number of excitations scales differently for large time across the speed of sound. Thus, our result dictates the critical behavior across Landau’s one and validates Landau’s intuition to the problem. We discuss how Landau’s critical velocity emerges and its validity within our model [1].

References

Structure factor of ultra-cold bosons in two-dimensional optical lattices

Tomasz Zaleski, Tadeusz Kopec

1. Institute of Low Temperature and Structure Research, PAS, ul. Okólna 2, 50-422 Wroclaw, Poland

We study the structure factor of the interacting ultra-cold atoms in a square optical lattice. Using a combined Bogoliubov method and the quantum-rotor approach, the Bose-Hubbard Hamiltonian of strongly interacting bosons is mapped onto the U(1)-phase action. This allows to calculate the momentum and energy dependence of the structure factor in the presence of the Mott insulator and superfluid phases. It is shown that superfluidity manifests itself as a sharp coherence peak resulting from the emergence of the long-range order. On the other hand, correlation effects lead to the appearance of a smearing of the excitation spectra of incoherent particles although the remnants of the Bogoliubov band are still present in the part linked to coherent particles.
Quantum state for zero mode of cold atomic gas system with Bose-Einstein condensate

Yusuke Nakamura¹, Junichi Takahashi¹, Yoshiya Yamanaka¹

1. Department of Electronic and Photonic Systems, Waseda University, Tokyo 159-8555, Japan

The quantum state of the zero mode of Bose-Einstein condensate is investigated from the standpoint of quantum field theory. The existence of the condensate, which is associated with the spontaneous breakdown of the global phase symmetry, must involve the zero mode according to the Nambu-Goldstone theorem [1]. However, the zero mode is often neglected (ex. Bogoliubov approximation) because of its infrared singular property. To remove the singularity and handle the zero mode in quantum field theoretical manner, we propose a new unperturbed Hamiltonian [2], which includes not only the first and second powers of the zero mode operators but also the higher ones, and obtain a non-singular stationary quantum state which is appropriate as the vacuum of the condensed system. Using the quantum state, we calculate physical quantities of the condensed system, such as the phase fluctuation, both at zero and finite temperatures.

References
Two-particle coalescences for the helium-like ions.

Evgeny Liverts

1. Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

The two-electron Schrödinger equation at the two-particle coalescences was studied for the atomic three-body systems in S-states [1]. The general differential equation in three variables was reduced to the centrally symmetric field problem for the case of electron-nucleus and electron-electron coalescence lines. New potentials describing attractive and repulsive interactions between the coalesced pair of the electron and nucleus, and the two coalesced electrons, respectively, were derived and studied. Interesting features of these potentials in the vicinity of the triple coalescence point were found. The ground states of the helium atom, the positive ion of hydrogen and the negative ion of lithium were explored, as the typical examples of the helium isoelectronic sequence.

References

Full control over two interacting fermions in a single double well

Simon Murmann1, Andrea Bergschneider1, Vincent M. Klinkhamer1, Gerhard Zürn1, Thomas Lompe1,2, Selim Jochim1

1. Physikalisches Institut der Universität Heidelberg, INF 226, 69120 Heidelberg, Germany
2. Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA

We have deterministically prepared two fermions in a single double-well potential, having full control over the two-particle quantum state. Starting with two non-interacting atoms in the ground state of a single potential well we can either rapidly switch on a second well and observe tunneling dynamics, or access eigenstates of the double well by means of an adiabatic passage.

After preparing both particles in the ground state of the double well, we introduce interparticle interactions and measure their influence on the particle statistics. For repulsive interactions we find a strong enhancement of singly occupied sites which can be understood as a two-particle analogy to a Mott-insulator. For attractive interactions we observe the onset of the charge-density-wave regime. In a spectroscopic measurement, we study how second-order tunneling affects the energy of the system.

By combining several double-well systems we aim for a bottom-up approach to many-body Hubbard physics.
Ultracold mixtures of metastable He and Rb: scattering lengths from ab initio calculations and thermalization measurements

S. Knoop1, P. S. Zuchowski2, D. Kedziera3, L. Mentel4, M. Puchalski5, H. P. Mishra1, A. S. Flores1, W. Vassen1

1. LaserLaB, Department of Physics and Astronomy, VU University, Amsterdam, The Netherlands
2. Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Torun, Poland
3. Department of Chemistry, Nicolaus Copernicus University, Torun, Poland
4. Section of Theoretical Chemistry, Department of Chemistry, VU University, Amsterdam, The Netherlands
5. Faculty of Chemistry, Adam Mickiewicz University, Poznan, Poland

We have investigated the ultracold interspecies scattering properties of metastable triplet He (He*) and Rb. Ultracold or quantum degenerate He*+Rb mixtures are interesting for few-body physics that require a large mass ratio, such as the observation of multiple Efimov loss features. We performed state-of-the-art ab initio quantum chemistry calculations of the relevant interaction potential, and measured the interspecies elastic cross section for an ultracold mixture of 4He* and 87Rb at a temperature of 0.5 mK in a quadrupole magnetic trap. Our combined theoretical and experimental study gives an interspecies scattering length \( a_{4+87} = +17^{+1}_{-4} a_0 \), which prior to this work was unknown. More general, our work shows the possibility of obtaining accurate scattering lengths using ab initio calculations for a system containing a heavy, many-electron atom, such as Rb.

References
Efimov Resonances in a Mixture with Extreme Mass Imbalance

Juris Ulmanis¹, Rico Pires¹, Stephan Häfner¹, Marc Repp¹, Alda Arias¹, Eva D. Kuhnle¹, Matthias Weidemüller¹, ²

¹. Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
². Hefei National Laboratory for Physical Sciences at the Microscale, University of Science and Technology of China, Hefei, Anhui 230026, PR China

We present the observation of two consecutive heteronuclear Efimov resonances in an ultracold Fermi-Bose mixture of Li-Cs by measuring magnetic field dependent three-body loss coefficients and atom loss spectra near a broad Feshbach resonance [1]. The first Efimov resonance is found at a scattering length of $a(0)=-320(10)a_0$, corresponding to approximately 7(3) times the Li-Cs (Cs-Cs) van der Waals range. The second resonance appears at $a(1)=-1870(390)a_0$, close to the unitarity-limited regime at the sample temperature of 450 nK. Indication of a third resonance is found in the atom loss spectra. The scaling factor of the resonance positions of 5.8(1.0) is close to the predicted universal value of 4.9 for zero temperature mixtures. The refined Feshbach resonance position agrees excellently with an extensive interpretation of the recently observed interspecies Li-Cs Feshbach resonances [2] by three different theoretical models: coupled channels calculation, asymptotic bound state model, and multi-channel quantum defect theory.

References

The influence of confinement, dimensionality, and anisotropy on effective multibody interactions of trapped ultracold bosons.

P.R. Johnson¹, E. Tiesinga², D. Blume³

¹. American University, Washington DC
². Joint Quantum Institute, NIST and University of Maryland
³. Washington State University

Effective multibody interactions can play an important role in the physics of ultracold atoms in optical lattices. Their influence is seen in both the non-equilibrium dynamics of quenched systems, and in precision measurements of atomic Mott-insulator states. Recent studies also suggest they can be used to generate exotic quantum phases. We will discuss our analysis of the effective three- and four-body interactions generated by both contact and effective range two-body interactions. We will also present new results for 1D, 2D isotropic, and 3D cylindrically symmetric harmonic potentials which illustrate the role of confinement and dimensionality on effective interactions, and which may be useful for ultracold atom experiments in highly anisotropic traps.
Towards optical Feshbach resonances with $^{40}$Ca

Evgenij Pachomow$^1$, Max Kahmann$^1$, Uwe Sterr$^1$, Fritz Riehle$^1$, Eberhard Tiemann$^2$

1. Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany
2. Institute of Quantum Optics, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany

Ultra-cold quantum gases of alkaline earth elements Ca, Sr and Yb have been the subject of photoassociation investigation due to their narrow singlet-triplet intercombination lines. Of these, calcium offers the narrowest intercombination line with a natural linewidth of 374 Hz only. A quantum degenerate $^{40}$Ca gas [1] has been produced in our experiment using forced evaporation in an optical dipole trap. We plan to employ this narrow line for manipulating the scattering length through optical Feshbach resonances (OFR). Compared to the experiments with Yb [2] and Sr [3], where the atom loss limited the possible interaction time, the small linewidth of calcium should reduce the corresponding losses. The binding energies of the most weakly bound molecular states in the relevant potentials were recently measured by single-colour photoassociation spectroscopy and described by a coupled channel model [4]. Based on the model and experimental data we estimated the feasibility of OFR.

References

Long range interactions of Sr and Yb in mixed quantum gases.

Sergey G. Porsev$^1$, Marianna S. Safronova$^{1,2}$, Andrei Derevianko$^3$, Charles W. Clark$^2$

1. Department of Physics & Astronomy, University of Delaware, Newark, Delaware 19716, USA
2. Joint Quantum Institute, NIST and the University of Maryland, Gaithersburg, Maryland 20899, USA
3. Physics Department, University of Nevada, Reno, Nevada 89557, USA

A first-principles relativistic method is developed for the accurate calculation of van der Waals coefficients of dimers involving excited-state atoms with a strong decay channel to the ground state. Accurate values of these long-range interaction parameters are needed for efficient production, cooling, and control of molecules. We used the developed methodology to calculate a number of $C_6$ and $C_8$ coefficients for Sr-Sr, Yb-Yb, Yb-Rb, and Yb-Li dimers which are of particular interest for development of optical lattice clocks, studies of quantum gas mixtures, and practical realization of quantum simulation proposals. Our calculations include $C_6$ coefficients for the Sr-Sr and Yb-Yb $^1S_0+^3P_0^0$ and $^3P_0^0+^3P_0^0$ dimers, $C_8$ coefficients for the $^1S_0+^1S_0$ and $^1S_0+^3P_0$ dimers, $C_6$ coefficients for the Yb-Rb $^3P_0^0+(5s ~^2S_{1/2})$ and $^1S_0^0+(5p ~^2P_{1/2})$ dimers, and the $C_8$ coefficients for the Yb-Li $^1S_0^0+(2s ~^2S_{1/2})$ and Yb-Rb $^1S_0^0+(5s ~^2S_{1/2})$ dimers. We perform detailed uncertainty analysis and provide stringent bounds on all quantities.
The Degenerate Unitary Bose Gas

Xin Xie1, Catherine Klauss1, Eric Cornell1, Deborah Jin1

1. JILA, NIST and University of Colorado at Boulder

A degenerate Bose gas with fully unitary interactions is generally inaccessible due to its short lifetime at large scattering lengths. However, we observe a metastable state of ultracold trapped $^{85}$Rb gas at shorter timescales than the three-body losses. With time-resolved measurements of the momentum distribution of a Bose Condensed gas that suddenly jumps to unitarity, we find that the gas has momentum-dependent dynamics consistent with a universal relation with sample density, while still remaining degenerate. This work opens the door for experimental investigation of unitary regime, thus builds the foundation for future explorations of intriguing strongly interacting quantum liquid.

References
Dipolar gases of ground state molecules: NaK in Hannover

Alessandro Zenesini\textsuperscript{1}, Torben A. Schulze\textsuperscript{1}, Ivo I. Temelkov\textsuperscript{1, 2}, Matthias W. Gempel\textsuperscript{1}, Torsten Hartmann\textsuperscript{1}, Horst Knöckel\textsuperscript{1}, Silke Ospelkaus\textsuperscript{1}, Eberhard Tiemann\textsuperscript{1}

\textsuperscript{1}. Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany

\textsuperscript{2}. Department of Physics, Sofia University, 5 James Bourchier Boulevard, 1164 Sofia, Bulgaria

In the coming years, dipolar interactions will be one of the most promising tools in the field of ultracold atoms. Since the first realization of degenerate gases of dipolar atoms and the creation of large diatomic molecular samples in their rovibrational groundstate \cite{ref1}, a lot of experimental and theoretical interest has been focused on long-range interactions, anisotropy, exotic phase transitions and other peculiar phenomena. We will update you on our work in Hannover with details on the NaK experimental apparatus and on our effort to determine the most efficient adiabatic transfer from weakly-bound dimers to ground state dipolar molecules \cite{ref2}.

References
Precision measurements with ultracold Sr$_2$ molecules in optical lattices

Bart McGuyer$^1$, Mickey McDonald$^1$, Geoffrey Iwata$^1$, Marco Tarallo$^1$, Tanya Zelevinsky$^1$

1. Department of Physics, Columbia University, 538 West 120th Street, New York, New York 10027-5255, USA

We present high-resolution studies of subradiant states and asymptotic physics with ultracold strontium dimers in an optical lattice. The molecules are photoassociated from $^{88}$Sr atoms near a narrow intercombination line. High-Q molecular spectra uncover peculiar physics, including multiply forbidden optical transitions that can be observed just below the atomic threshold. We measure and describe the natural lifetimes of subradiant states in terms of radiative and nonradiative contributions. Near the atomic asymptote, anomalously large linear, quadratic, and higher-order Zeeman shifts are observed. Measurements of linear Zeeman shifts yield nonadiabatic mixing angles of the molecular wave functions. We strongly enable forbidden transitions using small magnetic fields and for the first time, quantitatively compare electric- and magnetic-dipole as well as electric-quadrupole transition strengths in molecules. To characterize the ultranarrow molecular transitions, it is necessary to engineer magic optical lattices where state insensitivity is achieved via polarization and wavelength tuning. Current and future work made possible by this new type of long-lived molecule is discussed.

Rf-induced association of ultracold molecules in $^{87}$Rb.

Iurii Mordovin, Alessandro Brolis, Mikhail Egorov, Brenton Hall, Andrei Sidorov

1. Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne, Victoria 3122, Australia

Recently two papers [1], [2] proposed radiofrequency-induced coupling of atomic scattering states with a bound molecular state to induce Feshbach resonances at arbitrary magnetic fields. We report the first observation of predicted resonances for a mixture of two states $|1, -1>$ and $|2, +1>$ in $^{87}$Rb. Sudden increase of atom losses in narrow ranges of rf-frequencies clearly indicates the molecule association. We successfully created diatomic molecules in five different bound states and mapped their energies in the magnetic field range from 0.15 to 3.3 Gauss. From the interpolated data we determine zero-magnetic field energies of molecules with high precision (uncertainty is better than 0.1%). We also worked out a simple theory on the molecule formation rate and developed an explanation for observed asymmetries of observed resonant curves. New method of molecule association can be employed with any other mixtures of atoms and used for creation and studying new molecules.

References
Photoassociative production of Feshbach molecules of ytterbium by using the ultranarrow $^1S_0$-$^3P_2$ transition

Shintaro Taie$^1$, Shunsuke Watanabe$^1$, Shuta Nakajima$^1$, Hideki Ozawa$^1$, Tomohiro Ichinose$^1$, Yoshiro Takahashi$^1$

1. Kyoto University

Feshbach resonance, which is one of the most important experimental tools for ultracold atoms, is not available in the ground state of Yb. Recently it was found that Feshbach resonances exist between the ground $^1S_0$ and the excited metastable $^3P_2$ states [1]. In this poster, we will present the production of $^1S_0+^3P_2$ Feshbach molecules and determination of their bound energies by means of photoassociation. For fermionic $^{171}$Yb, we find 11 resonances below 8G, which are considered to be induced by the presence of anisotropic interactions [2]. We succeed to create Feshbach molecules for these resonances via photoassociation. Enhanced Franck-Condon factor in the vicinity of Feshbach resonances enables to easily observe the ultranarrow photoassociation resonances. These resonances will also provide the way to tune the scattering length between the ground states by means of optical Feshbach resonances with greatly suppressed atom loss.

References

Isotopic analysis of Na-K Feshbach resonances and molecules

Andrea Simoni$^1$, Alexandra Viel$^1$

1. Institut de Physique de Rennes, UMR 6251 CNRS-Université de Rennes 1, 35042 Rennes Cedex, France

We study theoretically magnetically induced Feshbach resonances and near-threshold bound states in isotopic Na-K pairs. Our calculations accurately reproduce Feshbach data on Na-K(40) and explain the origin of unusual observed multiplets in the p-wave [1]. We apply the model to predict scattering and threshold bound state properties of the boson-boson Na-K(39) and Na-K(41) systems. We find that the Na-K(39) isotopic pair presents favorable properties for producing non-reactive ground state polar molecules by stimulated photoassociation schemes.

References
Ultracold molecules: far-from-equilibrium quantum magnetism
Kaden Hazzard\textsuperscript{1}, Michael Foss-Feig\textsuperscript{2}, Ana Maria Rey\textsuperscript{3}

\textsuperscript{1}. JILA, CU-Boulder and Rice University
\textsuperscript{2}. JQI, NIST, University of Maryland
\textsuperscript{3}. JILA, CU-Boulder

Recent experiments with ultracold molecules in optical lattices have realized strongly interacting spin-1/2 models and probed their non-equilibrium dynamics. I will discuss theoretical methods that we have developed to understand this dynamics, the comparison with experiment, and theoretical predictions. In some cases, these new techniques offer a dramatic increase in accuracy with respect to previously available methods.

COOLING AND TRAPPING OF ATOMS AND IONS

A dual species magneto-optical trap of Cs and Yb
Ruben Freytag\textsuperscript{1, 2}, Stefan Kemp\textsuperscript{1}, Kirsteen Butler\textsuperscript{1}, Stephen Hopkins\textsuperscript{1}, Michael Tarbutt\textsuperscript{2}, Simon Cornish\textsuperscript{1}, Jeremy M. Hutson\textsuperscript{1}, Edward Hinds\textsuperscript{2}

\textsuperscript{1}. Durham University
\textsuperscript{2}. Imperial College London

The potentials of ultracold polar molecules have been discussed in many areas, including quantum computation and cold quantum chemistry. This experiment aims to produce an optical lattice of ground state Caesium-Ytterbium molecules. Compared to bi-alkali molecules, CsYb should have an additional magnetic dipole moment, which enables spin dependent interactions on a lattice [1,2]. Using methods such as magnetic-association over a Feshbach resonance [3] and Stimulated Raman Adiabatic Passage (STIRAP) [4], we aim to associate ultracold clouds of Yb and Cs to ground state molecules. We present a dual species magneto-optical trap of Caesium and Ytterbium loaded with a single Zeeman slower, as well as some theoretical background to the project.

References
Two-Stage Magneto-Optical Trapping of $^6$Li Using D2 Line and Narrow-Line Cooling to High Phase-Space Density

Jimmy Sebastian$^1$, Christian Gross$^1$, Ke Li$^1$, Huat Chai Jaren Gan$^1$, Wenhui Li$^1$, Kai Dieckmann$^1$

1. Centre for Quantum Technologies (CQT) and National University of Singapore, 3 Science Drive 2, Singapore 117543

Recently, laser cooling techniques applied to alkali atoms have been revisited. Improved cooling is of particular interest for the isotopes of lithium and potassium, where standard D2 line laser cooling does typically not result in temperatures below the Doppler limit. Sub-Doppler temperatures have been achieved by the method of gray molasses for $^{39}$K, $^{40}$K, and $^7$Li [1-3] and by employing far-detuned light for $^7$Li [4]. Low temperatures have also been achieved by laser cooling employing narrow transitions to higher optically excited states for $^{40}$K, $^{41}$K, and $^6$Li [5,6]. We report on results where we load $^6$Li atoms into a magneto-optical trap (MOT) on the D2 transition before transfer into a narrow-line MOT at 323nm. We present our cooling and compression scheme that results in a temperature of 33μK and a comparatively high phase-space density of 3x10^{-4}, which is an ideal starting point for further evaporative cooling in an optical trap.

References

Grey-molasses cooling of an optically trapped Fermi gas

Graham Edge, Stefan Trotzky, Stefan Trotzky, Stefan Trotzky, Stefan Trotzky, Joseph Thywissen

1. University of Toronto

Robust sub-Doppler cooling has recently been demonstrated at the D1 (nS_{1/2} to nP_{1/2}) transition of potassium [1-3] and lithium [4], atoms that are challenging to cool on the D2 cycling transition. Two mechanisms are at work: first, Sisyphus cooling in the standing-wave dipole potential, at least partially due to polarization gradients [1]; second, velocity-selective coherent population trapping (VSCPT) in a superposition of the two hyperfine ground states [2-4]. We extend this technique to the cooling of dense clouds in optical traps. Since the VSCPT dark state relies only on ground-state coherences, it is insensitive to optical shifts from far-detuned optical traps. We also observe that the molasses has sufficient cooling power to withstand light scattering on the 4S-5P transition. Together these observations indicate that D1 cooling is a promising approach to fluorescence imaging of single fermions in an optical lattice.

References

Dual isotope magneto-optical trap with only one laser beam

Saeed Hamzeloui, Victor Valenzuela, Monica Gutierrez, Eduardo Gomez

1. Universidad Autónoma de San Luis Potosí
2. Universidad Autónoma de Sinaloa

Magneto-optical traps (MOTs) are the starting point for many experiments in atomic physics. Alkali atom (in our case Rb) MOTs are quite common, and they require the use of two lasers, i.e., the trap and the repumper lasers. Here we demonstrate a dual isotope magneto-optical trap using a single diode laser [1]. We generate all the optical frequencies needed for trapping both species using a fiber intensity modulator. All the optical frequencies are amplified simultaneously using a tapered amplifier. The independent control of each frequency is on the RF rather than on the optical side. This introduces an enormous simplification for laser-cooling applications that often require at least one acousto-optic modulator for each laser beam. Additional isotopes can be simply added by including extra RF frequencies to the modulator and beams for other uses can be produced the same way.

References
Magneto-optical traps for Yb, Tm, Er, and Ho loaded from a buffer-gas beam source

Eunmi Chae1, 2, Boerge Hemmerling1, 2, Garrett K. Drayna2, 3, Aakash Ravi1, 2, John M. Doyle1, 2

1. Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
2. Harvard-MIT Center for Ultracold Atoms, Cambridge, Massachusetts 02138, USA
3. Department of Chemistry, Harvard University, Cambridge, Massachusetts 02138, MA

We report the first magneto-optical trap (MOT) loaded from a buffer-gas beam source [1, 2]. We demonstrate the unique flexibility of our source by loading MOTs for Yb, Tm, Er, and Ho, without any additional slowing stages. Residual helium background gas results in a maximum trap lifetime of 80 ms (with Yb). The addition of a single frequency slowing laser achieves an unprecedentedly high loading rate of 2.0(1.0)*10^10 Yb atoms/s and 1.3(0.7)*10^8 Yb atoms in the MOT. Our approach could be useful for species that preclude the use of a Zeeman slower, e.g. molecules, or for experiments where high atom number or throughput are critical.

We plan to use this buffer-gas beam source to load a MOT with CaF using laser cooling and slowing similar to that used with YO and SrF [3, 4].

References

Neutral Gas Sympathetic Cooling of an Ion in a Paul Trap

Kuang Chen1, Scott Sullivan1, Eric Hudson1

1. Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA

A single ion immersed in a neutral buffer gas is studied. An analytical model is developed that gives a complete description of the dynamics and steady-state properties of the ions. An extension of this model, using techniques borrowed from the mathematics of finance, is used to explain the recent observation of non-Maxwellian statistics for these systems. Taken together, these results offer an explanation of the longstanding issues associated with sympathetic cooling of an ion by a neutral buffer gas.

References
Quantum interactions in a hybrid atom-ion trap

Steven Schowalter¹, Christian Schneider¹, Alex Dunning¹, Kuang Chen¹, Prateek Puri¹, Seth Linker¹, Eric Hudson¹

¹. University of California, Los Angeles

Using a hybrid trap, interactions between laser-cooled atoms and ions and sympathetically-cooled molecular ions are studied. Our hybrid trap consists of ⁴₀Ca magneto-optical trap localized within a linear quadrupole trap used to create Coulomb crystals of various ionic species such as Yb⁺, Ba⁺, and BaCl⁺. Ultracold collisions in this hybrid trap allow the characterization of novel interactions important to quantum and astro-chemistry. Additionally these collisions serve as a robust and general method to create samples of ground state molecular ions with large dipole moments, which serves as a significant milestone towards using molecular ions in quantum information studies as well as potential qubits in future quantum computation architecture. Here we discuss our current efforts to quantify certain charge-exchange reactions; observe and simulate the complex dynamics of trapped ions in an ultracold buffer gas; and demonstrate the ro-vibrational quenching of the non-vertical molecular ion BaCl⁺ using a highly-polarizable, ultracold buffer-gas of calcium atoms.
Advancing surface-electrode ion trap capabilities: demonstrations of ball grid arrays, active in-vacuum control electronics, and integrated diffractive optics

Jason Amini\(^1\), Curtis Volin\(^1\), Chris Shappert\(^1\), Harley Hayden\(^1\), C.S. Pai\(^1\), Nicholas Guise\(^1\), Spencer Fallek\(^1\), Kenton Brown\(^1\), True Merrill\(^1\), Alexa Harter\(^1\), Lisa Lust\(^2\), Doug Carlson\(^2\), Jerry Budach\(^2\), Kelly Muldoon\(^2\), Alan Cornett\(^2\), Dave Kielpinski\(^3\), Daniel Youngner\(^4\), Matthew Marcus\(^4\)

1. Georgia Tech Research Institute
2. Honeywell International (IEMIT collaboration)
3. Griffith University (IDM collaboration)
4. Honeywell International (SMIT-BGA collaboration)

We report on three IARPA seedling projects that address issues in scaling of microfabricated ion traps to large numbers of qubits. In the first project (SMIT-BGA), Honeywell International has fabricating gold surface-electrode ion traps with back-side ball-grid-array connections to eliminate wirebonds and to reduce the physical die size. We demonstrate ion loading and transport and provide characterizations of the trap operation. The second project (IEMIT), also in collaboration with Honeywell International, is a successful demonstration \([1]\) of a compact, in-vacuum 80 channel DAC system controlling a surface-electrode ion trap. This system reduces the number of through vacuum connections by a factor of ten. The third project (IDM), in collaboration with Griffith University, takes multiple diffractive optical elements and etches them into the surface of a surface-electrode ion trap. We demonstrate reflective optical elements for both collimation and refocusing of light from \(^{171}\text{Yb}^+\).

References

* This material is based upon work supported by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA) under U.S. Army Research Office (ARO) contracts W911NF1210605 and W911NF1210600 and under Space and Naval Warfare Systems (SPAWAR) contract N6600112C2007.

Nano-friction between crystals of light and ions with atomic resolution and control from one- to many-body physics

Alexei Bylinskii\textsuperscript{1, 2, 3}, Dorian Gangloff\textsuperscript{1, 2, 3}, Vladan Vuletic\textsuperscript{1, 2, 3}

\textsuperscript{1.} Massachusetts Institute of Technology
\textsuperscript{2.} MIT-Harvard Center for Ultracold Atoms
\textsuperscript{3.} Research Laboratory of Electronics

Friction is a ubiquitous phenomenon poorly understood at the nano-scale, where large forces dominate across atomically smooth interfaces. We study stick-slip friction – the catastrophic energy release mechanism dominant in this regime – with previously unattainable atomic resolution and control in a synthetic nano-friction interface between a Coulomb crystal of cold trapped ions and a crystal of light, an optical lattice. We tune stick-slip friction from maximal to zero, the sought after regime of superlubricity, via lattice mismatch of the two crystals by controlling the ion arrangement. We also vary the size of the Coulomb crystal from one to many ions, elucidating the connection between the single-particle and many-particle minimalistic models of nano-friction. Interestingly, we observe the transition to superlubricity, a many-particle interaction effect, with only 3 ions. The possibility of correlated quantum tunneling makes this a promising system for studying novel quantum many-body phases and dynamics of nano-friction.
‘Alligator’ photonic crystal waveguides for single-atom trapping and strong light-matter interactions

S.-P. Yu1, 2, J. D. Hood1, 2, J. A. Muniz1, 2, M. J. Martin1, 2, Richard Norte2, 3, C.-L. Hung1, 2, Sean M. Meenehan2, 3, Justin D. Cohen2, 3, Oskar Painter2, 3, H. Jeff Kimble1, 2

1. Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, CA 91125, USA
2. Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, CA 91125, USA
3. Thomas J. Watson, Sr., Laboratory of Applied Physics 128-95, California Institute of Technology, Pasadena, CA 91125, USA

Recent advances in nanophotonics provide new possibilities for optical physics [1-2]. The integration of free-space atoms with nanophotonic devices has progressed on several fronts, including nano-scale cavities [3] and dielectric waveguides [4]. Significant technical challenges exist for developing such hybrid atom-photonic systems, arising from the following requirements: (1) The fabrication is sufficiently precise to match waveguide photonic properties to atomic spectral lines; (2) atoms are stably trapped in the presence of substantial Casimir-Polder forces yet achieve strong atom-field interaction; (3) coupling to and from guided modes of nanophotonic elements is efficient; (4) sufficient optical access exits for external laser cooling and trapping; and (5) sufficient optical power handling capability to support trap depths ~ 1mK. We describe a novel ‘alligator’ photonic crystal waveguide that meets these stringent requirements for integration of nanophotonics with ultracold atom experiments [5]. We also discuss progress toward dynamic capacitive tuning of the PCW band structure.

References
Injection of angular momentum in a polariton superfluid

Quentin Glorieux\textsuperscript{1}, Thomas Boulier\textsuperscript{1}, Giacobino Elisabeth\textsuperscript{1}, Alberto Bramati\textsuperscript{1}, Hugo Tercas\textsuperscript{2}, Dmitry Solnyshkov\textsuperscript{2}, Guillaume Malpuech\textsuperscript{2}

\textsuperscript{1.} Laboratoire Kastler Brossel - ENS Paris - UPMC - CNRS, France
\textsuperscript{2.} Institut Pascal, PHOTON-N2, Blaise Pascal University, France

We report the formation of a ring-shaped array of vortices after injection of angular momentum in a polariton superfluid. A $L=8$ Laguerre-Gauss mode is generated using an holographic technique on a spatial light modulator, and the angular momentum is transferred to the fluid via quasi-resonant excitation.

We can distinguish two interesting regimes. For low power excitation (low density of polaritons) we observe a spiral pattern containing phase defects, signature of optical interferences. On the other hand, in the high density regime the interaction between polaritons become relevant and the interference disappears while vortices nucleate as a consequence of the angular momentum quantization. The radial position of the vortices evolves freely as a function of the density. Hydrodynamic instabilities resulting in the spontaneous nucleation of vortex-antivortex pairs when the system size is sufficiently large confirm that the vortices are not constrained when nonlinearities dominate the system.
Observation of Grand-canonical Number Statistics in a Photon Bose-Einstein condensate

Julian Schmitt¹, Tobias Damm¹, David Dung¹, Frank Vewinger¹, Jan Klaers¹, Martin Weitz¹

1. Institute for Applied Physics, University of Bonn, Wegelerstr. 8, 53115 Bonn, Germany

Large statistical number fluctuations are a fundamental property known from the thermal behavior of bosons. At low temperatures, when a macroscopic fraction of bosonic particles undergoes Bose-Einstein condensation, large fluctuations of the condensate population conflict with particle number conservation. Correspondingly, condensation is accompanied by a damping of fluctuations and the emergence of second-order coherence. Here, we report measurements of particle number correlations and fluctuations of a photon Bose-Einstein condensate in a dye microcavity. The photon gas is coupled to a reservoir of molecular excitations, which serve as both heat bath and particle reservoir to realize grand-canonical conditions. For large reservoirs, we observe strong number fluctuations of the order of the total particle number extending deep into the condensed phase. Our results demonstrate that condensation under grand-canonical ensemble conditions does not imply second-order coherence. We find a regime where Bose-Einstein condensation and statistical fluctuations as large as the particle number coexist.

References

Light-Wave Mixing and Scattering with Quantum Gases

L. Deng¹, C. J. Zhu², E. W. Hagley¹

1. NIST, Gaithersburg, USA 20899
2. East China Normal University, Shanghai, China 200062

We show that optical processes originating from elementary excitations with dominant collective atomic recoil motion in a quantum gas can profoundly change many nonlinear optical processes routinely observed in a normal gas. Not only multi-photon wave mixing processes all become stimulated Raman or hyper-Raman in nature but the usual forward wave-mixing process, which is the most efficient process in normal gases, is strongly reduced by the condensate structure factor. On the other hand, in the backward direction the Bogoliubov dispersion automatically compensates the optical-wave phase mismatch, resulting in efficient backward light field generation that usually is not supported in normal gases.

References
Sympathetic cooling of a membrane oscillator in a hybrid mechanical-atomic system

Tobias Kampschulte\textsuperscript{1}, Andreas Jöckel\textsuperscript{1}, Aline Faber\textsuperscript{1}, Lucas Beguin\textsuperscript{1}, Maria Korppi\textsuperscript{1}, Matthew T. Rakher\textsuperscript{1}, Philipp Treutlein\textsuperscript{1}

\textsuperscript{1}Department of Physics, University of Basel, Switzerland

Sympathetic cooling with ultracold atoms and atomic ions enables ultralow temperatures in systems where direct laser or evaporative cooling is not possible. So far, it has only been used to cool other microscopic particles such as atoms of a different species or molecular ions up to the size of proteins [1].

Here we use ultracold atoms to sympathetically cool the vibrations of a Si\textsubscript{3}N\textsubscript{4} membrane, a microfabricated structure which is currently used in many optomechanics experiments [2]. The atoms and the membrane vibrations are coupled via laser light over a macroscopic distance [3]. An optical cavity around the membrane enhances the interactions [4], allowing us to efficiently cool the membrane vibrations from room temperature to $650 \pm 330$ mK [5].

Our hybrid optomechanical system [6] operates in a regime of large atom-membrane cooperativity and enables a number of exciting experiments on quantum control of mechanical motion.

References

Optical Frequency Combs and Temporal Solitons in Optical Microresonators

J. D. Jost¹, T. Herr¹, V. Brasch¹, M. H. P. Pfeiffer¹, M. L. Gorodetsky², ³, T. J. Kippenberg¹

1. École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
2. Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow 119991, Russia
3. Russian Quantum Center, Skolkovo, 143025, Russia

The field of frequency metrology was revolutionized by the invention of the optical frequency comb (OFC) [1]. Later in 2007 it was discovered that OFCs can also be generated in optical microresonators [2,3], which typically have a large spacing between comb lines (10GHz to 1THz), large power per frequency comb line, and spectra in the near-infrared or the mid-infrared. However, until recently the noise often present in these OFCs made them unsuitable for frequency metrology applications. We demonstrate that low noise OFCs can be achieved via soliton formation in Magnesium Fluoride and Silicon Nitride optical microresonators [4]. This also has been shown in Magnesium Flouride optical microresonators to provide pulses which can be used to externally broaden OFCs to sufficient bandwidths for self-referencing.

References

Self-organized optomechanical structures

Thorsten Ackemann¹, Guillaume Labeyrie², Enrico Tesio¹, Pedro Gomes¹, Gian-Luca Oppo¹, William J. Firth¹, Gordon R. M. Robb¹, Aidan S. Arnold¹, Robin Kaiser²

1. SUPA and Department of Physics, University of Strathclyde, Glasgow G4 0NG, Scotland, UK
2. Institut Non Lineaire de Nice, UMR 7335 CNRS, 1361 route des Lucioles, 06560 Valbonne, France

We demonstrate the spontaneous emergence of hexagonal structures in a laser beam traversing a cloud of cold Rb atoms and being retro-reflected by a single plane mirror. The pump axis is the only distinguished axis and spontaneous breaking of the rotational as well as translational symmetry in the plane orthogonal to this axis is demonstrated. Light patterns and atomic density patterns are complementary: Hexagonally coordinated light peaks expel atoms due to dipole forces leading to the formation of a matching honeycomb structure in the atomic density. The scattering of the pump light at the resulting density grating sustains in turn the modulation of the light field. The length scale is given by the Talbot effect. The experiment opens novel options for the manipulation and control of matter as well as studying symmetry breaking and dynamical phase transitions in a well controlled system which can be potentially transferred to quantum matter.

References
Feedback cooling using a near-Heisenberg-limited position measurement

Dalziel Wilson¹, Vivishek Sudhir¹, Nicolas Piro¹, Ryan Schilling¹, Amir Ghadimi¹, Tobias Kippenberg¹

¹. École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Near-field cavity-optomechanical coupling [1,2] is used to continuously monitor the position of a 4.3 MHz nanomechanical oscillator with an imprecision ~ 30 dB below that at the standard quantum limit. Employing this measurement as a feedback signal, radiation pressure is used to cold damp [3] the oscillator from a cryogenic bath temperature of 15 K to an effective temperature of ~ 2 mK, corresponding to a mean phonon occupation of \( n \sim 10 \). The inferred product of the measurement imprecision and the force noise experienced by the oscillator is ~ 20 times above the limit set by the Heisenberg uncertainty principle [4]. These results underscore the potential of cavity optomechanics as a toolbox for quantum feedback control.

References

Optomechanics with ultra cold Rydberg gases

Sebastian Wüster¹, Adrian Sanz-Mora¹, Alexander Eisfeld¹, Jan-Michael Rost¹

¹. Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Strasse 38, 01187 Dresden, Germany

Ultra cold gases in which atoms are coupled to highly excited Rydberg states are emerging as versatile platform for interdisciplinary research, realizing single photon sources [1], extremely non-linear Kerr media [2], quantum gates [3] or aggregate systems to study conical intersections [4] and energy transport [5]. We investigate the exploitation of such features interface a Rydberg gas with a micro mechanical oscillator. In our model system, a vibrating mirror is coupled to a medium with electromagnetically induced transparency (EIT) via the probe and coupling laser beams. Dramatic effects of Rydberg excitations on the EIT medium [1,2] allow intricate interplay between Rydberg physics and mirror mechanics.

References
Cavity Opto-Mechanics with Cold Atoms: Force Sensing near the Standard Quantum Limit and Coupled Oscillators

Nicolas Spethmann¹, Jonathan Kohler¹, Sydney Schreppler¹, Dan Stamper-Kurn¹

¹. Department of Physics, University of California, Berkeley

Cavity Opto-Mechanics with cold atoms provides a system with unique properties for studying quantum physics: Highly tunable and controllable oscillators, close to their thermal groundstate, with excellent isolation from the environment and quantum-limited optical detection.

The limit of sensitivity of a force measurement dictated by quantum mechanics, the Standard Quantum Limit, is reached when measurement imprecision from photon shot-noise is balanced against disturbance from measurement back-action. To observe this quantum limit, we apply a known external force to the center-of-mass motion of an ultracold atom cloud in a high-finesse optical cavity. We achieve a sensitivity that is consistent with theoretical predictions and is a factor of 4 above the absolute Standard Quantum Limit.

The flexibility of our approach furthermore allows us to study cavity-optomechanics with multiple, coupled oscillators. To this end, we prepare two oscillators at distinct frequencies; off-resonance pumping of the cavity allows us to couple the oscillators and applying a force is employed to separately and coherently drive each oscillator. We observe the dynamics of this system both in the frequency and the time domain.

From membrane-in-the-middle to mirror-in-the-middle with a high-reflectivity sub-wavelength grating

Haitan Xu¹, ², Utku Kemitarak¹, ², Corey Stambaugh², Jacob Taylor¹, ², John Lawall²

¹. JQI UMD
². NIST

We fabricate highly reflective sub-wavelength grating membranes using silicon nitride. We achieve a grating reflectivity of 99.8% with a membrane mechanical frequency of ~1 MHz. We integrate the grating-membrane into a Fabry-Perot cavity and investigate its opto-mechanical properties.
A scanning cavity microscope

David Hunger\textsuperscript{1, 2}, Matthias Mader\textsuperscript{1, 2}, Thomas Hümmer\textsuperscript{1, 2}, Jonathan Noe\textsuperscript{1}, Matthias Hofmann\textsuperscript{1}, Alexander Högele\textsuperscript{1}, Christian Deutsch\textsuperscript{3}, Jakob Reichel\textsuperscript{3}, Theodor W. Hänsch\textsuperscript{1, 2}

\textsuperscript{1}. Faculty of Physics, Ludwig-Maximilians-University, 80799 Munich, Germany
\textsuperscript{2}. Max-Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
\textsuperscript{3}. Laboratoire Kastler Brossel, Ecole Normale Superieure / CNRS, 24 rue Lhomond, F-75005 Paris, France

We present a novel method for highly sensitive and spatially resolved absorption spectroscopy of nanoscale objects. To boost sensitivity, we harness multiple interactions of probe light with an object by placing the sample inside a high-Finesse scanning optical microcavity. The cavity is built from a laser-machined and mirror-coated end facet of a single mode fiber and a macroscopic plane mirror forming a fully tunable open access Fabry-Perot cavity \cite{1, 2}.

We present measurements with gold nanoparticles and carbon nanotubes which demonstrate a sensitivity for absorption cross sections down to \sim 1\text{nm}^2. We furthermore present a scheme harnessing the Purcell effect for cavity-enhanced Raman spectro-imaging. First results with individual single-wall carbon nanotubes are shown.

Our results open the perspective to use scanning cavity microscopy as a versatile tool for spectroscopy on weakly absorbing nanoparticles, for bio-sensing, and single-molecule studies.

References
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\cite{2} D. Hunger et al., AIP Advances 2, 012119 (2012)

Thermodynamic corrections to mechanical oscillations

Chiao-Hsuan Wang, Jacob M. Taylor

\textsuperscript{1}. Joint Quantum Institute, NIST and the University of Maryland

Optomechanics has been successfully applied to systems involving wide range of scales from as small as $10^{-21}$ g for atomic level objects like cold atoms to as large as $10^3$ g for macroscopic scale systems like LIGO project. As the size of the mechanical object gets larger, more degrees of freedom come in and the quantum harmonic oscillator treatment of optomechanics may become questionable. We examine models of a mechanical oscillator coupled to fermionic and bosonic degrees of freedom respectively, and find that spring-like classical oscillations can occur even if there is no underlying quantum mechanical oscillator. Methods for distinguishing between quantum harmonic oscillations and other oscillatory behavior are considered. Our model can be realized through potential implementations by using atoms as the spins and the optical cavity mode as the harmonic oscillator.
A Useful Entanglement Resource; 10 dB Spin Squeezing with Cavity QND Measurements

Kevin Cox¹, Justin Bohnet¹,², Matthew Norcia¹, Joshua Weiner¹, James Thompson¹

¹. JILA, NIST, and University of Colorado at Boulder
². National Institute of Standards and Technology, Boulder, Colorado

Entanglement can be used to increase measurement precision beyond the fundamental limit for an unentangled state, the so-called standard quantum limit. We present the direct observation of phase sensitivity 10.2(6) dB (factor of 10.5(1.5) in variance) below the standard quantum limit with no background subtractions applied. These results are achieved using quantum non-demolition measurements of a large atomic ensemble (5*10⁵ Rb atoms). By collectively probing the ensemble on an optical cycling transition, previously limiting sources of measurement back-action due to Raman transitions are greatly mitigated. The scheme demonstrated here is well-suited for use in optical lattice clocks, scales well with atom number, and avoids potential systematic errors due to atomic collisions.

Quantum metrology frontiers with highly squeezed quantum states of atomic ensembles

Onur Hosten¹, Rajiv Krishnakumar¹, Nils Engelsen¹

¹. Stanford University

Production of spin-squeezed atomic ensembles could greatly enhance the performance of existing atom-based sensors by overcoming the atomic shot-noise that limits these sensors. At the time of writing, our preliminary results with an ensemble of 25x10³ ⁸⁷Rb atoms (prepared in magnetically insensitive states) suggest a noise reduction that is 17dB below shot-noise with 90% coherence indicating a metrologically relevant squeezing parameter of 16.5dB. With our currently known experimental inefficiencies the theoretical maximum we expect to observe lies around 23dB for 100x10³ atoms.

We employ a measurement based squeezing method inside of a high-finesse (>10⁵) dual-wavelength cavity, resonant at both 780 nm (probe) and 1560 nm (trap). The commensurate wavelength relationship allows identical coupling of the probe light to all atoms, generating symmetric squeezed states, opening up the future possibility of releasing the generated states into free-space for fluorescence detection, compatible with atomic fountain based sensors.
Quantum Zeno dynamics of a Rydberg atom

Sebastien Gleyzes¹, Adrien Signoles¹, Adrien Facon¹, Eva-Katharina Dietsche¹, Igor Dotsenko¹, Serge Haroche¹, Jean-Michel Raimond¹, Michel Brune¹

1. Laboratoire Kastler Brossel, College de France, ENS, CNRS, UPMC, 11 Pl Marcelin Berthelot, F75231 Paris, France

The back-action of a quantum measurement can modify the evolution of a quantum system. The most famous example is the quantum Zeno effect, where the repeated measurements completely freeze the evolution. The behavior is different, however, if the eigenvalue corresponding to the result of the measurement is degenerated. In this case, the evolution of system is no longer freezed, but the dynamics is confined inside the corresponding eigenspace. This is the Quantum Zeno Dynamics (QZD).

We have experimentally implemented QZD in the Stark manifold of a Rydberg atom. Under the effect of a purely s+ polarized radio-frequency field, our atom initially in the circular state behaves as a J=25 spin, which rotates between the north and south poles of a generalized Bloch sphere. By repeatedly asking the system “have you crossed a given latitude?”, we can induce a very non classical evolution of the spin.

Generation of multiparticle entangled states using quantum Zeno dynamics

G. Barontini¹, L. Hohmann¹, F. Haas¹, J. Estève¹, J. Reichel¹

1. Laboratoire Kastler Brossel, ENS, UPMC-Paris 6, CNRS 24 rue Lhomond, 75005 Paris, France

Quantum states are usually generated by unitary operations exclusively, while interaction with the environment serves only for final measurement of the state, destroying its interesting properties. Powerful new forms of quantum dynamics have been proposed where this dichotomy is abandoned and environment coupling is used as part of the state generation. One incarnation of this general idea is quantum Zeno dynamics (QZD), where the system is coherently driven while simultaneously confining it to a subspace of its Hilbert space by a projective measurement. Using atom chips and fiber-optical cavities, we have applied QZD to create multiparticle entangled states in an ensemble of qubit atoms in a cavity. We perform quantum tomography of the resulting state and demonstrate that, in the presence of sufficiently strong measurement, the system attains a multiparticle entangled state instead of the separable state reached without the measurement.
**Many-particle entangled states of two-component Bose-Einstein condensates**

Roman Schmied\(^1\), Baptiste Allard\(^1\), Matteo Fadel\(^1\), Caspar Ockeloen\(^1\), Philipp Treutlein\(^1\)

1. Department of Physics, University of Basel, Switzerland

Many-particle entanglement is a fascinating concept that poses intellectual challenges and is at the heart of quantum computing, quantum simulation, and quantum metrology. Using controlled collisions on an atom chip\(^1\), we prepare different many-particle entangled states of two-component Bose-Einstein condensates, perform a tomography of their quantum state\(^2\), and explore their use in quantum metrology with an atom interferometer\(^3\). In recent experiments, we have created over-squeezed states, a class of non-Gaussian entangled states that are not spin-squeezed but still useful for atom interferometry beyond the standard quantum limit. Besides entanglement in a single Bose-Einstein condensate, our system could allow the generation of Einstein-Podolsky-Rosen entanglement of two spatially separated and individually addressable condensates\(^4\).

References


**Atomic twin Fock states in momentum space**

Raphael Lopes\(^1\), Almazbek Imanaliev\(^1\), Marie Bonneau\(^1\), Josselin Ruaudel\(^1\), Marc Cheneau\(^1\), Denis Boiron\(^1\), Christoph Westbrook\(^1\)

1. Laboratoire Charles Fabry, Institut d’Optique, CNRS

We report on our current work to establish a new source of atomic twin Fock state where the two modes consist of real-space momentum states instead of spin states. Since the entangled atoms fly apart of each other, such a source would enable the direct observation of non-locality with massive particles (instead of photons). Here, the two modes are the output channels of elastic collisions occurring in a Bose–Einstein condensate loaded in a moving optical lattice. Using metastable helium atoms and a microchannel plate detector, we are able to fully reconstruct the 3-dimensional momentum distribution of the output state with single atom resolution. Combined with the possibility to rotate the state on the Bloch sphere using Bragg pulses, this opens the route to a tomography of this highly non-classical state with excellent precision.
Quantum networking and sensing efforts at the Army Research Laboratory

Daniel Stack, David Meyer, Paul Kunz, Neal Solmeyer, Q. Quraishi

I. Quantum Sciences Group Army Research Laboratory Adelphi, MD 20783

The Quantum Sciences group at the Army Research Laboratory presents two ongoing efforts, an atom chip for ultra-cold atoms and a MOT-based quantum memory with PPLN frequency conversion for quantum networking.

The atom chip experiment explores the capabilities of ultra-cold/degenerate ensembles in a compact physics package. We use microwave and RF fields for coherent spin control of $^{87}\text{Rb}$ atoms. The atom chip enables tailoring magnetic trapping potentials, for studies of atom interferometery, novel quantum phases and quantum enhanced measurements.

Our quantum memory utilizes off-axis, spontaneously emitted single photons, generated by the interaction of a 795 nm write laser beam with cold $^{87}\text{Rb}$ atoms. To minimize optical fiber transmission losses, the single photons are frequency-converted to the telecomm band by difference frequency generation in a PPLN crystal. Quantum memories and single photon transport are key ingredients for a scalable quantum network that could enable high fidelity distribution of entanglement over long distances.

Towards the Detection of Momentum Entangled Atom Pairs

Michael Keller, Mateusz Kotyrba, Mario Rusev, Maximilian Ebner, Anton Zeilinger

1. Institute for Quantum Optics and Quantum Information (IQOQI) Vienna / University of Vienna

We present our work towards the creation and detection of momentum entangled states of metastable helium (He*) atoms.

Starting from a Bose-Einstein condensate (BEC) of metastable helium, stimulated Raman transitions transfer momentum onto the atoms. Subsequent collisions between two counterpropagating matter waves lead to atom pairs that are entangled in their momentum degree of freedom. This state represents a three-dimensional version of the one discussed in the Einstein-Podolsky-Rosen gedankenexperiment.

By using a position resolved micro-channel plate (MCP) detector the high internal energy of the He* atoms of almost 20 eV per atom allows for efficient detection of individual atoms with a high spatial and temporal resolution.

We show that a double double-slit as well as a ghost interference scheme can be used to show the entanglement and that those schemes are feasible with experimental restrictions in our setup. We discuss the main challenges in the experimental realization and present the present status of the experiment.
Control of Quantum Dynamics on an Atom-Chip

Ivan Herrera1, 2, Cosimo C. Lovecchio1, Florian Schäfer1, Shahid Cherukattil1, Murtaza Ali Khan1, Filippo Carusso1, Francesco Saverio Cataliotti1

1. European Laboratory for NonLinear Spectroscopy, Via Nello Carrara. 1, 50019, Sesto F.No(Fi), Italy
2. Centre for Quantum and Optical Science, Swinburne University of Technology, Melbourne, Victoria 3122, Australia

The minimization of the effect of external perturbations and, more importantly, the control of coherent dynamics within a conveniently defined quantum space is crucial to many applications such as atom interferometry and quantum information processing. We exploited the back action of quantum measurements and strong couplings to tailor and protect the coherent evolution of a quantum system, a phenomenon known as Quantum Zeno Dynamics. Furthermore we apply a recently developed optimal control tool to drive the quantum dynamics from initial state toward a chosen target. This tool allows to reach any point in the Hilbert space of interest, in a time much faster than allowed by non-optimized continuous coherent evolution. Our control and protection protocols are realized on a compact, easy to use, Atom-Chip device, using a 87Rb BEC, a system which simplifies the approach to future developments.

High-fidelity cluster state generation of ultracold atoms in an optical lattice

Yuuki Tokunaga1, Kensuke Inaba2, Kiyoshi Tamaki2, Kazuhiro Igeta2, Makoto Yamashita2

1. NTT Secure Platform Laboratories
2. NTT Basic Research Laboratories

We propose a method for generating high-fidelity multipartite spin entanglement of ultracold atoms in an optical lattice in a short operation time with a scalable manner, which is suitable for measurement-based quantum computation. To perform the desired operations based on the perturbative spin-spin interactions, we propose to actively utilize the extra degrees of freedom (DOFs) usually neglected in the perturbative treatment but included in the Hubbard Hamiltonian of atoms, such as, (pseudo-)charge and orbital DOFs. Our method simultaneously achieves high fidelity, short operation time, and scalability by overcoming the following fundamental problem: enhancing the interaction strength for shortening the operation time breaks the perturbative condition of the interaction and inevitably induces unwanted correlations among the spin and extra DOFs.

References
Coherent optical memory with 94% efficiency

Ya-Fen Hsiao¹, Pin-Ju Tsai¹, Chih-Hsi Lee¹, Hung-Shiue Chen¹, Yi-Hsin Chen², Ite A. Yu², Yong-Fan Chen³, Ying-Chen Chen¹,²

1. Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 10617, Taiwan
2. Department of Physics, National Tsing Hua University, Hsinchu 30043, Taiwan
3. Department of Physics, National Cheng Kung University, Tainan 70101, Taiwan

We report our experiment on the high-efficiency coherent optical memory based on electromagnetically induced transparency (EIT) scheme using optically dense cold cesium atoms. The optical depth for the EIT transition at the D₁ line is up to 650. Operation of the EIT at the D₁ line in addition with preparation of population in the single Zeeman state |F=3,m=3> eliminates the additional photon and atomic coherence losses due to the off-resonant coupling of the EIT control field to the unwanted excited states. This is crucial to obtain a high memory efficiency which requires to operate the EIT at high optical depths and strong control fields. At very high optical depth, the off-resonant coupling of the control field on the probe transition induces a four-wave mixing process which may result in the probe gain and introduce additional quantum noises. We discuss the effect of the four-wave mixing in our current experiment and in another related experiment, as well as the way to reduce the four-wave mixing.

RYDBERG ATOMS

Towards Single-Photon Nonlinear Optics via Pattern Formation in Spatially Bunched Atoms

Bonnie L. Schmittberger¹, Daniel J. Gauthier¹

1. Duke University Physics Department and Fitzpatrick Institute for Photonics

There is a great interest in enhancing light-atom interaction strengths to the point where injecting a single photon triggers a nonlinear optical response. Single-photon nonlinear effects are predicted to occur in a homogeneous gas of two-level atoms, but this has not been observed experimentally. We show theoretically that the nonlinearity that arises due to atomic bunching gives rise to more than two orders of magnitude enhancement in the third-order nonlinear optical susceptibility over the case of a homogeneous gas. With this enhanced material response, we predict that single-photon nonlinearities are attainable in sub-Doppler-cooled two-level atoms. We find that these results agree with our experimental observation of multimode, transverse optical pattern formation in sub-Doppler-cooled atoms, wherein we observe the intensity threshold to be two orders of magnitude lower than that reported for a homogeneous gas. With this ultra-low threshold, our system has the potential to realize a single-photon optical switch.
Optical properties of a strongly correlated array of induced dipoles

Robert Bettles¹, Simon Gardiner¹, Charles Adams¹

1. Department of Physics, Rochester Building, Durham University, South Road, Durham DH1 3LE, United Kingdom

We calculate the transmission of near resonant light through a monolayer of induced dipoles. Using classical-electrodynamics simulations we show that for a regular lattice, dipole-dipole interactions lead to departures from the Beer-Lambert law. In contrast to a quasi-2D ultracold random gas as modeled by authors in [1], the regular lattice displays strong correlation effects including ferro- and anti-ferroelectric phases which relate to super- and sub-radiant modes respectively. Such features could be observed using experimental cold atoms in optical lattices or metamaterials. We also highlight the significance of inhomogeneous broadening which destroys the correlations [2].

References

Photonic Controlled-Phase Gate Based on Rydberg Interactions

Mohammad Khazali, Khabat Heshami, Christoph Simon

1. Institute for Quantum Science and Technology and Department of Physics and Astronomy, University of Calgary, Calgary T2N 1N4, Alberta, Canada

Photons are ideal carriers of information in quantum communication. Since they do not interact, the implementation of deterministic photonic quantum computation depends on the creation of a non-permanent strong interaction between single photons. The implementation of neutral Rydberg atom gates [1] inspired the development of photonic gates, using the coherent reversible mapping of the quantum states of photons onto highly interacting Rydberg atoms [2-5]. Here we propose an interaction-based two-qubit gate between photons stored in Rydberg levels of an atomic ensemble. We perform a detailed study of errors due to the many-body interaction between Rydberg spin-waves, and we propose a compensation scheme for these errors. Furthermore we completely separate interaction and propagation by eliminating the Rydberg level from the storage process. Our proposed controlled-phase gate can achieve 99% fidelity with current technology.

References
Single-Photon Switch and Transistor Based on Rydberg Blockade

Stephan Duerr\textsuperscript{1}, Simon Baur\textsuperscript{1}, Daniel Tiarks\textsuperscript{1}, Katharina Schneider\textsuperscript{1}, Gerhard Rempe\textsuperscript{1}

1. Max-Planck-Institut f. Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

All-optical switching is a technique in which a gate light pulse changes the transmission of a target light pulse without the detour via electronic signal processing. We take this to the quantum regime, where the incoming gate light pulse contains only one photon on average \cite{1}. The gate pulse is stored as a Rydberg excitation in an ultracold gas using electromagnetically induced transparency. Rydberg blockade suppresses the transmission of the subsequent target pulse. Finally, the stored gate photon can be retrieved. A retrieved photon heralds successful storage. The corresponding postselected subensemble shows an extinction of 0.05. Using a Forster resonance, we achieve a gain of 20 for one incoming photon, thus demonstrating a single-photon transistor. The gain quantifies the change of the transmitted target photon number per incoming gate photon. The detected target photons reveal in a single shot with fidelity above 0.86 whether a Rydberg excitation was created during the gate pulse \cite{2}.

References
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Strongly Interacting Photons in a Rydberg Polariton Gas: Few Photon Spectroscopy and Coulomb Bound States

M. J. Gullans¹, M. F. Maghrebi¹, I. Martin³, O. Firstenberg², S. Choi², P. Bienias⁴, H. P. Buchleitner², M. D. Lukin², A. V. Gorshkov¹

¹. Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, College Park, Maryland 20742, USA
². Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA
³. Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
⁴. Institute for Theoretical Physics III, University of Stuttgart, Germany

Free space photons can be made to strongly interact by converting them into dark state polaritons dressed with Rydberg atoms. Recently a two-photon bound state was experimentally observed in such systems [1]. Here we discuss the zoology of two-photon bound states and scattering states that emerge in this system. We show how to efficiently measure the full two-photon scattering matrix using a series of pulsed experiments. We use this method to characterize the fidelity of two-photon gates in this system. We then consider a special class of bound states that emerge when the Rydberg interaction brings the two polaritons into Raman resonance. We show that these exotic bound states have the spectrum of a 1D Coulomb bound particle. Furthermore, these "Coulomb" states travel with negative group velocity, which allows a simple preparation and detection scheme. We demonstrate the backward propagation, preparation, and detection of Coulomb states with full numerical simulations.

References
Generating topological spin textures in spinor Bose-Einstein condensates by a stimulated Raman interaction

Azure Hansen¹, ², Justin T. Schultz¹, ³, Nicholas P. Bigelow¹, ², ³

¹. Center for Coherence & Quantum Optics, University of Rochester, Rochester, NY USA
². Department of Physics & Astronomy, University of Rochester, Rochester, NY USA
³. The Institute of Optics, University of Rochester, Rochester, NY USA

Here we present the generation of spin monopoles, non-Abelian vortices, skyrmions, fractional vortices, coreless vortices, and singular vortices in an ⁸⁷-Rb Bose-Einstein condensate. A coherent Raman process allows us to engineer the internal and external momenta, superfluid velocities, and spatial spin distribution of the condensate as well as control the complex relative phases of the magnetic spin components. Using techniques from singular optics we can generate complex laser beams and therefore a great diversity of spin textures and topological excitations in the BEC. This optical imprinting also permits, for example, multiple monopoles to exist in a single BEC, enabling the study of monopole-anti-monopole dynamics. Studying the behavior of these spin textures provides insight into other fields, furthers understanding of fundamental spin-dependent symmetries and light-matter interactions, and extends applications of ultracold atomic physics to metrology and information.
**Stability of a Floquet Bose-Einstein condensate in a one-dimensional optical lattice**

Sayan Choudhury\(^1\), Erich Mueller\(^1\)

\(^1\) Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York

Motivated by recent experimental observations (C.V. Parker et al., Nature Physics, 9, 769 (2013)), we analyze the stability of a Bose-Einstein condensate (BEC) in a one-dimensional lattice subjected to periodic shaking. In such a system there is no thermodynamic ground state, but there may be a long-lived steady-state, described as an eigenstate of a “Floquet Hamiltonian”. We calculate how scattering processes lead to a decay of the Floquet state. We map out the phase diagram of the system and find regions where the BEC is stable and regions where the BEC is unstable against atomic collisions. We show that Parker et al. perform their experiment in the stable region, which accounts for the long life-time of the condensate (∼ 1 second). We also estimate the scattering rate of the bosons in the region where the BEC is unstable.

**References**


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**Topological phases in spin-orbit coupled dipolar bosons in a one-dimensional lattice**

Ho-Tsang Ng

1. Institute for Interdisciplinary Information Sciences, Tsinghua University

We study the spin-orbit coupled dipolar bosons in a one-dimensional optical lattice. In the Mott-insulating regime, this system can be described by the quantum XYZ spin model in a transverse field. The magnetic dipolar interactions between atoms give rise to the inter-site interactions. We focus on investigating the effect of dipolar interactions on the topological phase. The topological phase can be shown when spin-orbit coupling incorporates with the repulsive dipolar interaction. We find that the dipolar interactions can broaden the range of parameters of SO coupling and transverse field for exhibiting the topological phase. We investigate the spin correlations between the two nearest neighbour atoms for indicating the topological phase. This may be useful for detecting topological phases in experiments.
Fractionalized Majorana fermions (parafermions) with ultracold atoms

Mohammad Maghrebi\textsuperscript{1}, Sriram Ganeshan\textsuperscript{1}, Alexey Gorshkov\textsuperscript{1}, Jay Deep Sau\textsuperscript{1}

\textit{1. University of Maryland, and Joint Quantum Institute}

Parafermions are topologically protected modes which can be thought of as fractionalized Majorana fermions. They commute up to a nontrivial phase factor in contrast to the minus sign for fermions. It has been suggested that these exotic modes exist at the interface of a fractional quantum Hall system and a superconductor. In the light of recent advances towards the realization of fractional quantum Hall states with bosonic ultracold atoms, we propose a realization of parafermions in a system consisting of a Bose-Einstein-condensate trench within a bosonic fractional quantum Hall state. We show that parafermionic zero modes emerge at the endpoints of the trench and give rise to a topologically protected degeneracy. We also discuss methods for preparing and detecting these modes.

\textbf{Quantum Simulation Th-086}

\textbf{$p$-wave pair amplitude and $s$-wave superfluid phase transition in the BCS-BEC crossover regime of an ultracold Fermi gas with a spin-orbit interaction}

Tokitake Yamaguchi\textsuperscript{1}, Yoji Ohashi\textsuperscript{1}

\textit{1. Department of Physics, Keio University}

We theoretically investigate pairing properties of an ultracold Fermi gas with an $s$-wave pairing interaction and asymmetric spin-orbit coupling. In the $s$-wave superfluid state at $T=0$, we determine the parameter region where the broken spatial inversion symmetry due to the asymmetric spin-orbit interaction induces a large amount of $p$-wave pair amplitude. In this regime, a $p$-wave superfluid state is expected, when one suddenly changes the $s$-wave pairing interaction into the $p$-wave one using a Feshbach resonance. We also show that the region satisfying this regime has high phase transition temperature $T_c$, within the framework of the strong-coupling Gaussian fluctuation theory. Since the realization of a $p$-wave superfluid Fermi gas is an exciting challenge in cold Fermi gas physics, our results would be useful for realization of this unconventional pairing state using the recent artificial gauge field technique.

\textbf{Quantum Simulation Th-087}
Implementation, phase structure and real time dynamics in atomic quantum simulators of lattice Gauge-Higgs theory

Kenichi Kasamatsu¹, Yoshihito Kuno², Ikuo Ichinose², Tetsuo Matsui¹

¹. Department of Physics, Kinki University, Higashi-Osaka, Osaka 577-8502, Japan
². Department of Applied Physics, Nagoya Institute of Technology, Nagoya 466-8555, Japan

We propose how to implement a quantum simulator of the U(1) gauge-Higgs model with asymmetric nearest-neighbor Higgs coupling by using a system of cold atoms in an optical lattice [1]. The gauge-Higgs coupling in the imaginary time direction naturally arises from the violation of the U(1) local gauge invariance of the simulator caused by the deviation from the fine-tuned system parameters. A general method to supply the Higgs coupling in all space-time directions may be realized by coupling atoms in an optical lattice to another particle reservoir filled with the Bose-condensed atoms via laser transitions. Clarification of the dynamics of the gauge-Higgs model sheds some lights upon various unsolved problems including the inflation process of the early universe. We study the phase structure of this model by Monte Carlo simulations, and also discuss the real time dynamics of each phase through the analysis of the Gross-Pitaevskii model.

References
Collective mode analysis of a Bose-Einstein condensate in a density-dependent gauge potential

M. J. Edmonds¹, ², M. Valiente¹, P. Öhberg¹

1. SUPA, Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK
2. Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne NE1 7RU, England, UK

Synthetic gauge potentials created with Ultracold atomic gases have become the focus of intense interest both experimentally [1] and theoretically [2]. Most schemes are static in the sense that there is no feedback between the matter field and the method used to prescribe them. Here, we study the collective modes of a Bose-Einstein condensate subject to an optically induced density-dependent (interacting) gauge potential [3]. The excitation frequencies of the trapped one-dimensional condensate are obtained by solving the Bogoliubov-de Gennes equations as a function of the strength of the gauge field. It is found that at critical values of the gauge field strength the condensate exhibits dynamical instabilities. By studying the full nonlinear dynamics of this model, signatures of the instabilities can also be seen; including the departure of the dipole mode frequency from the trap frequency.

References

Synthetic Spin-Orbit Coupling Without Light

Brandon Anderson¹, Ian Spielman¹, Gediminas Juzeliūnas², Egidijus Anisimovas², André Eckhardt³

1. Joint Quantum Institute
2. Institute of Theoretical Physics and Astronomy, Vilnius University
3. Max-Planck-Institut für Physik komplexer Systeme

Recent experimental successes in Raman-induced spin-orbit coupling in ultracold atomic systems opened the door to the study of a novel class of many-body Hamiltonians. However, these techniques have been limited thus far to Abelian spin-orbit couplings. In this talk I will present a new technique for producing two- and three-dimensional non-Abelian (Rashba-like) spin-orbit couplings for ultracold atoms without involving light. Instead, a sequence of pulsed inhomogeneous magnetic fields imprint suitable phase gradients on the atoms. These techniques can be easily implemented on an atom chip. I will then consider the implementation of this spin-orbit coupling on a lattice. Exploiting the geometry of the atom-chip, both staggered and non-staggered non-Abelian fluxes can be induced. Finally, I demonstrate how combining the pulsed spin-orbit coupling with lattice shaking techniques can be used to produce Chern bands with C=2. Using exact diagonalization, we explore the novel Fractional Chern Insulating states that emerge in these models.

References
Self-organized Rice-Meile model in ultracold atoms

Anna Przysiężna\textsuperscript{1, 2}, Omjyoti Dutta\textsuperscript{4}, Jakub Zakrzewski\textsuperscript{3, 4}

1. Institute of Theoretical Physics and Astrophysics, University of Gdańsk, Wita Stwosza 57, 80-952 Gdańsk, Poland
2. National Quantum Information Centre of Gdańsk, Andersa 27, 81-824 Sopot, Poland
3. Instytut Fizyki imienia Mariana Smoluchowskiego, Uniwersytet Jagielloński, ulica Reymonta 4, 30-059 Kraków, Poland
4. Mark Kac Complex Systems Research Center, Uniwersytet Jagielloński, Kraków, Poland

One of the signatures of nontrivial topology in one-dimensional (1D) systems are solitons that exist on domain walls between topologically distinct phases. In the field of ultracold atoms it is, however, difficult to realize defects such as domain walls due to a perfect structure of optical trapping potentials. We show a 1D system of cold atoms in which a structure with nontrivial topological properties may emerge due to self organization. In this process of self organization defects that support solitons may be created. Our system consists of interacting two species fermions trapped in periodically driven lattice potential. Together, interaction and lattice shaking lead to the creation of density-wave structure of one species while the other species may be described with Rice-Meile model. We calculate configuration dependent Zak phase certifying the non-trivial topology and show existence of localized modes. We complement theoretical deriviations discussing experimental methods that may be used in order to probe topological phenomena.

Optical-lattice Floquet systems

Andre Eckardt

1. Max-Plnack-Institut für Physik komplexer Systeme, Nöthnitzer Str. 38, D-01187 Dresden, Germany

Ideas to engineer the Floquet Hamiltonian of periodically driven many-body systems have recently been successfully applied to optical-lattice systems. Examples include the dynamical control of the bosonic Mott transition in Arimondo's group and the realization of strong artificial gauge fields in the groups of Bloch, Esslinger, Ketterle, and Sengstock. I will discuss the dynamical realization of topological insulators in driven optical lattices and compare high-frequency approaches (like our proposal \cite{1}) with Floquet-topological-insulator schemes requiring intermediate frequencies (like the proposal \cite{2}). In this context also a method for the tomography of (topological) band insulators will be proposed \cite{3}. Moreover, I will present a careful study of how to selectively couple the lowest Bloch band of an optical lattice to a more dispersive excited band using resonant driving. Such orbital coupling is shown to allow for the coherent melting a bosonic ground-band Mott insulator into a (low-entropy) excited-band superfluid.

References

Measuring geometric phases in Bloch bands: The topology of a Dirac cone

Martin Reitter1, 2, Lucia Duca1, 2, Tracy Li1, 2, Monika Schleier-Smith3, Immanuel Bloch1, 2, Ulrich Schneider1, 2

1. Ludwig-Maximilians-Universitaet-Muenchen, Schellingstr. 4, 80799, Muenchen
2. Max-Planck-Institut for Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching
3. Stanford University, 450 Serra Mall, Stanford, CA 94305, United States

In addition to the dispersion relation, electronic bands are characterized by their topological properties, which give rise to intriguing phenomena such as the integer Quantum Hall effect or topological insulators. Using ultracold bosonic atoms in a graphene-type honeycomb lattice, we experimentally studied the local topological structure of individual Dirac points. By combining Bloch oscillations with Ramsey interferometry, we measured Berry phases for various closed loops in quasi-momentum space. When enclosing a single Dirac point, we observed a Berry phase of pi, while enclosing zero or two Dirac points resulted in a vanishing Berry phase. By imbalancing the lattice beams, we moved and subsequently merged the Dirac points in the Brillouin zone and characterized the resulting change in topological structure. Furthermore, we present preliminary measurements of interband topological properties using Stückelberg interferometry. These approaches can be applied to arbitrary lattices and can provide complete topological maps of the band structure.

Quantum magnetism of bosons with synthetic gauge fields in one-dimensional optical lattices: a Density Matrix Renormalization Group study

Marie Piraud1, Z. Cai1, I. P. McCulloch2, U. Schollwöck1

1. Department für Physik, LMU München, Theresienstrasse 37, D-80333 München, Germany
2. Centre for Engineered Quantum Systems, School of Physical Sciences, The University of Queensland, Brisbane, Queensland 4072, Australia

Significant effort is devoted to realize synthetic gauge fields for ultra-cold atoms in optical lattices. This permits to investigate strongly correlated Mott insulating phases, where the interplay between strong interactions and gauge fields can give rise to exotic quantum magnetism that is difficult to access in solid state physics. We provide a comprehensive study of the quantum magnetism in the Mott insulating phases of the 1D Bose-Hubbard model with Abelian or non-Abelian synthetic gauge fields, using DMRG. We focus on the interplay between the synthetic gauge field and the asymmetry of the interactions, which gives rise to a very general effective magnetic model: a XYZ model with various Dzyaloshinskii-Moriya interactions, which are strongly reminiscent of those present in strongly correlated electronic materials. The properties of the different quantum magnetic phases and phase transitions of this model are investigated.
Synthetic fields in synthetic dimensions

Benjamin K. Stuhl1, 2, Lauren Aycock2, 3, Hsin-I Lu2, 4, Dina Genkina2, 5, Ian B. Spielman1, 2, 4

1. National Institute of Standards and Technology, Gaithersburg, MD
2. Joint Quantum Institute, College Park, MD
3. Cornell University, Ithaca, NY
4. University of Maryland Department of Physics, College Park, MD

The combination of ultracold atomic gases with optically-induced synthetic gauge fields promises a potent new experimental tool. In the context of lattice-type physics, large synthetic magnetic fields offer the chance to experimentally probe such fascinating systems as insulating phases with chiral edge states and nontrivial Chern numbers, and the fractal Hofstadter butterfly spectrum. To avoid the heating issues associated with large Raman-coupling rates, we treat the Zeeman quantum number of each atom as an index in an effective 1-D lattice and combine that with optical Raman coupling and a 1-D real-space optical lattice to produce the dynamics of a spinless 2-D lattice gas in a homogeneous magnetic field.

Topologically Robust Transport of Photons in a Synthetic Gauge Field

S. Mittal1, 2, J. Fan1, S. Faez4, A. Migdall1, J. M. Taylor1, M. Hafezi1, 2

1. Joint Quantum Institute, University of Maryland / National Institute of Standards and Technology, Gaithersburg
2. Department of Electrical and Computer Engineering, University of Maryland, College Park
3. Huynghs-Kammerlingh Onnes Laboratorium, Universiteit Leiden, Netherlands

We implement a synthetic gauge field for photons using a two-dimensional lattice of coupled micro-ring resonators, on a silicon photonics platform. We demonstrate the presence of topologically robust edge states in our system using direct imaging of the edge state wavefunction. Using transmission and delay measurements made on a number of devices, we further show that the edge states are less susceptible to fabrication induced disorder when compared to bulk states. Also, the edge state transport is diffusive whereas the bulk states are localized. Moreover, we compare the transmission along edge states to a topologically trivial one-dimensional system and unambiguously demonstrate the robustness of edge states.

References
Atomic Hong-Ou-Mandel effect in tunnel-coupled optical tweezers

Adam Kaufman1, 2, Brian Lester1, 2, Collin Reynolds1, 2, Michael Wall1, 2, Michael Foss-Feig3, Kaden Hazzard1, 2, Ana Maria Rey1, 2, Cindy Regal1, 2

1. JILA, National Institute of Standards and Technology and University of Colorado
2. Department of Physics, University of Colorado, Boulder, Colorado 80309, USA
3. Joint Quantum Institute and the National Institute of Standards and Technology, Gaithersburg, Maryland, 20899, USA

We present recent work in which we demonstrate near-complete control over all the internal and external degrees of freedom of single laser-cooled 87Rb atoms trapped in sub-micron optical tweezers. By dynamically introducing a tunnel-coupling between the tweezers, we implement a massive-particle analog of the Hong-Ou-Mandel effect where atom tunneling plays the role of the photon beamsplitter. The HOM effect is used to probe the influence of atomic indistinguishability on the two-atom dynamics for a variety of initial conditions. These experiments demonstrate the viability of the optical tweezer platform for bottom-up generation of low-entropy quantum systems and provide an alternative route toward direct observation of quantum dynamics in tunable finite-sized systems.

Quantum co-walking of two interacting particles in one-dimensional lattices

Xizhou Qin1, Yongguan Ke1, Chaohong Lee1

1. State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics and Engineering, Sun Yat-Sen University, Guangzhou 510275, China

We investigate continuous-time quantum walks of two indistinguishable particles (bosons, fermions or hard-core bosons) with nearest-neighbor interactions in one-dimensional lattices. The two interacting particles can undergo independent and/or co-walking dependent on both quantum statistics and the interaction strength. We find that for a strong interaction the two particles may form a bound state as a pair of co-walkers that behave like a single composite particle with quantum statistics dependent propagation speed. Such an effective single-particle picture of co-walking is analytically derived in the context of perturbation and consistent with numerical result. In addition to observing bound state, two-particle quantum walks offer a novel detect for exploring quantum statistics and spin dynamics. The two-particle quantum walks in our models can be simulated by light propagations in waveguide arrays or spin-impurity dynamics of ultracold atoms in optical lattices.

References
Direct Observation of Strongly Correlated Bosonic Quantum Walks

Ruichao Ma¹, Philipp Preiss¹, M. Eric Tai¹, Alex Lukin¹, Matthew Rispoli¹, K. Rajibul Islam¹, Markus Greiner¹

¹. Department of Physics, Harvard University

Quantum coherence, quantum statistics, and strong interaction between particles are the key components of strongly correlated quantum matter. With the single-site detection and addressing abilities in our quantum gas microscope, we demonstrate a bottom-up approach to engineer strongly correlated matter, and realize single particle and strongly correlated two-particle quantum walks in one dimension. We detect single particle quantum walks and position space Bloch oscillations with exceptional quantum coherence, and observe the crossover from strong bunching to anti-bunching as the bosons fermionize due to strong repulsive interactions. We create repulsively bound atom pairs and study their coherent dynamic. Our work constitutes a new level of control over few-body states in optical lattices and will enable state engineering in quantum simulation and quantum information processing applications.

In situ probing of interacting fermions in an optical lattice

Eugenio Cocchi¹, ², Jan Drewes², Luke Miller¹, ², Ferdinand Brennecke², Marco Koschorreck², Daniel Pertot², Michael Koehl¹, ²

¹. Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB30HE, United Kingdom
². Physikalisches Institut, University of Bonn, Wegelerstrasse 8, 53115 Bonn, Germany

The Fermi Hubbard model, despite its formal simplicity, contains intriguing physics and poses questions regarding quantum magnetism and d-wave superconductivity which have not been answered yet. The possibility of realizing this model with ultracold fermions in optical lattices has paved the way to many fascinating experiments.

We experimentally investigate the Fermi Hubbard model by locally probing its phases. We prepare a degenerate Fermi gas of potassium-40 atoms and load it into a three-dimensional optical lattice. Our high resolution imaging system combined with a selective RF transfer allows us to independently image the in situ density profiles of the atoms in doubly or singly occupied lattice sites. Varying the on-site interaction by means of a Feshbach resonance we can explore the phases of the Fermi Hubbard model. I will report on our steps towards the local characterisation of the transition to a Mott insulator state.
**Fermi Gas Microscope with Lithium-6**

Maxwell Parsons¹, Florian Huber¹, Anton Mazurenko¹, Christie Chiu¹, Sebastian Blatt¹, Markus Greiner¹

1. Harvard-MIT Center for Ultracold Atoms and Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

We present the first site-resolved images of fermionic lithium-6 atoms in an optical lattice. Lithium’s light mass and its broad Feshbach resonance provide fast and controllable many-body dynamics. The light mass also gives the atoms a large recoil energy, making it difficult to scatter many photons while keeping the atoms pinned at their lattice sites. In addition, lithium has unresolved hyperfine structure in the excited $2P_{3/2}$ state, precluding the use of the polarization gradient cooling used in rubidium single-site experiments. We solve these problems with pulsed Raman sideband cooling in a 2.5 mK deep optical lattice with $\sim 1$ MHz trap frequencies at 566 nm spacing and detect the resonantly scattered light to produce images with 520 nm resolution. Quantum gas microscopy with bosonic atoms has enabled direct observation of local correlations [1] and site-resolved manipulation [2] in optical lattices and led to new studies of quantum phase transitions and many-body dynamics. Our work opens the door to local probing and control of systems with fermionic statistics.

**References**


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**Quantum gas microscope of ytterbium atoms**

Martin Miranda¹, Yuki Okuyama¹, Ryotaro Inoue¹, Mikio Kozuma¹

1. Tokyo Institute of Technology

Our group focuses on the development of a quantum gas microscope using ytterbium atoms[1,2]. Ytterbium atoms have zero electronic spin, and thus, provide much longer coherence time compared to that of alkali atoms, and are a good candidate for a quantum computer [3].

To increase the numerical aperture of the system, we introduced a solid immersion lens (SIL) between the Yb atomic cloud and the objective lens. Atoms were transported to the surface of the solid immersion lens using a system comprised by three optical dipole traps and the optical accordion technique. After being transported, a pancake-shaped two-dimensional condensate was created near the surface of the SIL [4]. Later, two optical accordion beams (1080 nm wavelength) were retro-reflected, trapping the atoms in a square lattice with a 540 nm period. Fluorescence images with single-site resolution of the atoms trapped in the two-dimensional optical lattice were successfully obtained.

**References**

Experimental demonstration of more than 100 individually addressable qubits for quantum simulation and quantum computation

Malte Schlosser¹, Sascha Tichelmann¹, Felix Stopp¹, Daniel Ohl de Mello¹, Gerhard Birkl¹

¹ Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt, Germany

Efficient quantum simulation and quantum information processing requires scalable architectures that guarantee the allocation of large-scale qubit resources. In our work, we focus on the implementation of multi-site geometries based on microfabricated optical elements. This approach allows us to develop flexible, integrable and scalable configurations of multi-site focused beam traps for the storage and manipulation of single-atom qubits and their interactions [1]. We give an overview on the investigation of ⁸⁵Rb atoms in two-dimensional arrays of well over 100 individually addressable dipole traps featuring trap sizes and a tunable site-separation in the single micrometer regime. Furthermore, we experimentally demonstrate single-atom quantum registers with more than 100 occupied sites, single-site resolved addressing of single atom quantum states in a reconfigurable fashion and discuss progress in introducing Rydberg based interactions in our setup.

References
Qubit fidelity of a single atom transferred among the sites in a ring lattice

Shi Yu¹,²,³, Peng Xu¹,², Min Liu¹,², Jin Wang¹,², Mingsheng Zhan¹,²

1. State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China
2. Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China
3. University of Chinese Academy of Sciences, Beijing 100049, China

Controlled transfer of atomic qubits opens a route towards quantum information storage and processing. We demonstrate transfer among single atoms trapped in sites of the ring lattice with the aid of an auxiliary moving optical tweezer [1]. Atom in one site follows the moving tweezer when it crosses the lattice and is transported to another site with high efficiency of 95%. In comparison with other schemes [2, 3], it is applied more conveniently for single atoms array. Quantum state tomography is performed to obtain qubit fidelity during the transfer. Additionally, we investigate the coherence properties and analyze in details via spin echo techniques. The reduced fidelity results from instabilities of the tweezer and heating of atoms.

References
Coherent dipole-dipole coupling between two single atoms at a Förster resonance

Sylvain Ravets, Henning Labuhn, Daniel Barredo, Thierry Lahaye, Antoine Browaeys

1. Laboratoire Charles Fabry, UMR 8501, Institut d’Optique, CNRS, Univ Paris Sud 11, 2 avenue Augustin Fresnel, 91127 Palaiseau Cedex, France

Resonant energy transfers, the redistribution of an electronic excitation between two particles coupled by the dipole-dipole interaction, occur in a variety of chemical and biological phenomena [1], most notably photosynthesis. Here, we study, both spectroscopically and in the time domain, the coherent, dipolar induced exchange of electronic excitations between two single Rydberg atoms separated by a controlled distance, and brought in resonance by applying electric or microwave fields [2]. The coherent oscillation of the system between two degenerate pair states occurs at a frequency that scales as the inverse third power of the distance, the hallmark of dipole-dipole interactions [3]. We finally study the propagation of an excitation in a three-atom system. These results show our ability to actively tune strong, coherent interactions in quantum many-body systems.

References

A 2D array of Rydberg coupled atomic qubits

Martin Lichtman1, Michal Piotrowicz1, Michal Piotrowicz1, Tian Xia1, Larry Isenhower1, Mark Saffman1

1. University of Wisconsin - Madison

We are developing a 2D array of optically trapped single atom qubits for quantum computation experiments. We demonstrate stochastic loading of an average of 30 Cs atom qubits in a 49 site array with 3.8 μm site to site spacing. Parallel qubit rotations are performed with microwaves and site selective single qubit gates are demonstrated using focused beams of two-frequency Raman light. Single qubit gate fidelity is characterized with randomized benchmarking. Using Rydberg excitation and blockade we demonstrate entanglement of pairs of trapped atoms, and will report on progress towards running quantum algorithms in the array.
The 4d⁸ - 4d⁷(4f +6p) transitions of In VI

Swapnil,1, Ahmad Tauheed¹

1. Department of Physics, Aligarh Muslim University, Aligarh-202002, India

The sixth spectrum of indium (In VI) has been investigated in the grazing incidence wavelength region. The spectrum was recorded on 10.7-m grazing incidence spectrographs at National Bureau of Standards Laboratory in Washington D.C. The source used was a sliding spark operated at different discharge currents. The ground configuration of In VI is 4p⁶4d⁸ and the excited configurations are of the type 4d⁷n(n≥4). Joshi and VanKleef [1, 2] reported 4d, 4d⁷5p and 4d⁷5s configurations. In the present work, the 4d⁸ - 4d⁷(4f+6p) transition array has been studied using Hartree-Fock calculations with relativistic corrections by Cowan’s code, incorporating the other interacting configurations 4d⁷(5p+5f)+4p⁵(4d⁹+4d⁸5s) for odd parity matrix. More than 75 new energy levels have been established so far based on the identification of about 230 spectral lines. Our wavelength accuracy in the 190 - 400Å region is ±0.005Å. Final interpretation will be based on the least squares fitted parametric calculations.

References

Photoionizing ¹⁷⁴Yb⁺ to ¹⁷⁴Yb²⁺

Simon Heugel¹, ², Martin Fischer¹, ², Markus Sondermann¹, ², Gerd Leuchs¹, ², ³

1. Max Planck Institute for the Science of Light, Erlangen, Germany
2. Friedrich-Alexander University Erlangen-Nürnberg (FAU), Department of Physics, Erlangen, Germany
3. Department of Physics, University of Ottawa, Canada

We report on the photoionization of ¹⁷⁴Yb⁺ ions trapped inside a radio-frequency ion-trap. The photoionization is realized in a three-step scheme. In the second intermediate step the 4f¹⁴7p₁/₂ level in ¹⁷⁴Yb⁺ is excited via the transition from the 4f¹⁴5d₃/₂ level with a cw-laser at 245 nm. Another photon at 245 nm finally provides the energy for the ionization. A laser at 976 nm is applied continuously in order to clear the long-lived 4f¹⁴5d₅/₂ level. The photoionization is typically achieved with intensities of 10 W/cm² at 245 nm. Effects from stray charges created by this laser can thereby be minimized. The ¹⁷⁴Yb²⁺ ions are identified using crystallized mixed-species ion-pairs: The effect of a ¹⁷⁴Yb²⁺ 'guest' ion onto the position of a ¹⁷⁴Yb⁺ 'host' ion as well as the motional resonance-frequencies of this two-ion crystal are detected, unambiguously indicating for the successful ionization.
Precision frequency measurement of transitions between singlet states in atomic helium

Pei-Ling Luo1, 2, Jin-Long Peng3, Li-Bang Wang2, Jow-Tsong Shy1, 2

1. Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30013, Taiwan
2. Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
3. Center for Measurement Standards, Industrial Technology Research Institute, Hsinchu 30011, Taiwan

We report the precision frequency measurement of transitions between singlet states in atomic helium, including the 21S0-21P1 transition at 2058 nm [1] and the 21P1-31D2 transition at 668 nm [2]. Our measured transition frequencies can be combined with the theoretical ionization energy of 3D states and other precisely measured transitions to obtain the ionization energies of the 21S0 and 21P1 states. These results should provide crucial tests for atomic calculations and stimulate new theoretical developments of the singlet states in atomic helium. More importantly, our determined ionization energy of the 21P1 state in 4He shows a discrepancy of approximately 3.5σ with the currently most precise theoretical calculation.

References
Interactions of charged particles with atoms and molecules are of immense importance since they provide information about the collision dynamics involved in the delicate quantum mechanical process. Particularly, the reactions involving electrons are of prime importance in diverse areas, few of them may be listed as plasma physics, radiation damage in biological tissue. The pioneer work of Ehrhardt et al. [1] showed a pathway to obtain detailed information on the dynamics of an electron impact single ionization (e, 2e) process through a kinematically complete experiment. Following the work of Ehrhardt et al. [1], which provides full momentum information of both the outgoing electrons, many kinematically complete (e, 2e) studies have been done on a wide variety of geometrical and kinematic arrangements for various atomic targets. Theoretical descriptions for the electron impact single ionization of hydrogen and helium atoms have been very successful using non-perturbative approaches such as convergent close coupling [2], exterior complex scaling [3] and time dependent close coupling [4]. Problems still persist for electron impact ionization of more complex targets and even for the simple two electron target helium near the threshold regime.

We report in this communication the fully differential cross section (FDCS) results for the double ionization of helium atoms in the threshold regime at 5 eV excess energy. We calculate FDCS in the second Born approximation and also include post collision interaction (PCI) between two ejected electrons in the theoretical treatment. We compare our theoretical results with the measurements of Ren et al. [5]. The post collision interaction (PCI) has been found to be instrumental in describing the trends of FDCS.

References
The dynamical properties of autoionization of rare-earth Eu atom

Chang-jian Dai¹, Cheng Dong¹, Hong-rui Liang¹

1. College of Science, Tianjin University, of Technology, Tianjin 300384, China

The velocity-map-imaging method is employed to investigate experimentally the dynamical process of ejected electrons from Eu 4f⁷6s⁶p¹/₂⁸s autoionizing states. The atom is stepwise excited from the 4f⁷6s⁶s⁸S⁷/₂ ground state to the 4f⁷6s⁸s⁸P⁷/₂ Rydberg state via the 4f⁷6s⁶p⁶P⁵/₂ intermediate state, then excited further to the 4f⁷6p¹/₂(\(J=3\))⁸s and 4f⁷6p¹/₂(\(J=4\))⁸s autoionizing states with the three-step isolated-core excitation method.

The ejected electron from the autoionizing process can be focused and imaged by the electron lens. The kinetic energy of which is resolved by the position sensitive detector. Combining velocity-map-imaging method with the mathematical transformation, the velocity of ejected electron can be determined, yielding both energy and angular distributions of it. By tuning the wavelength of the third laser across the autoionization resonance, the variation characteristics of the asymmetric parameters and branching ratio are observed. The possibility of the population inversion due to autoionization has been discussed.

Enantiomer-specific detection of chiral molecules via microwave spectroscopy

David Patterson¹,², Sandra Eibenberger³, Melanie Schnell⁴, John M. Doyle¹,²

1. Department of Physics, Harvard University
2. Harvard-MIT Center for Ultracold Atoms
3. University of Vienna, Faculty of Physics, VCQ & QuNaBioS, Vienna, Austria
4. Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany

We recently devised and demonstrated a definitive, large signal, mixture compatible spectroscopic method for the determination of the chirality of molecules. Three-wave mixing with signals enhanced through the use of cold molecules provides the phase sensitive enantiomeric signal [1,2]. Either buffer-gas or supersonic beam cooling can provide high molecular internal state phase space densities [3]. Here we present further developments of the technique, demonstrating sensitivity at the 1% enantiomeric excess level using the novel RABBIT geometry spectrometer. The addition of enhanced spectroscopic techniques should yield unprecedented chiral sensitivity, and progress toward this is described.

References
Theoretical transition rates of forbidden lines in doubly-ionized iron group elements

Vanessa Fivet$^1$, Pascal Quinet$^{1,2}$, Manuel Bautista$^3$

1. Astrophysique et Spectroscopie, Université de Mons - UMONS, B7000 Mons, Belgium
2. IPNAS, Université de Liège, B4000 Liège, Belgium
3. Department of Physics, Western Michigan University, Kalamazoo MI 49008, USA

Accurate fine-structure atomic data for the Fe-peak elements (Sc, Ti, V, Cr, Mn, Fe, Co and Ni) are essential for interpreting astronomical spectra currently available. The lowly-ionized spectra of several iron group elements have been observed in nebular and stellar environments [1-2]. Yet, our present knowledge of their atomic structure is lagging behind the avalanche of high-quality spectra arising from these ions. We present our systematic approach for studying the electronic structures and radiative rates of forbidden lines of doubly-ionized iron peak elements. The magnetic dipole (M1) and electric quadrupole (E2) transition probabilities are computed using the pseudo-relativistic Hartree-Fock (HFR) code of Cowan [3] and the central Thomas-Fermi-Dirac-Amaldi potential approximation implemented in AUTOSTRUCTURE [4] using a new method of optimization for the potential scaling parameters. The extensive sets of results obtained using these two theoretical approaches are then compared to the rare experimental and theoretical data available in the literature for these ions in order to assess the advantages and shortcomings of each method and provide astrophysicists with a comprehensive set of reliable radiative data.

References
Second Spectrum of Selenium

Ahmad Tauheed1, Hala 1

1. Physics Department, Aligarh Muslim University, Aligarh - 202002, India

We investigated the spectrum of singly ionized selenium (Se II) and found serious irregularities in the published results [1]. Our investigation was based on the study of 4s^24p^3 • [4s^24p^2 (4d+5d+5s+6s)+4s4p^4] transition array. The previously reported analysis has been revised extensively. Out of fifty-two reported levels, thirteen were rejected and new level values were found. Since the mean energies of 4s^24p^24d and 4s4p^4 configurations differ only by 2000 cm\(^{-1}\) therefore, the proximity of the two configurations result in the strong mixing of levels. The earlier reported levels given without designation or configuration assignments are now well interpreted with Hartree-Fock calculations. Apart from even parity configurations, similar designations were also given for odd parity levels. Consequently, we also extended our investigation to include 4s^24p^25p and 4s^24p^24f configurations. Almost all the levels of 4p^25p configuration have been found but the study of 4p^24f is still under progress and the latest findings will be presented in the conference.

References
High-precision nonadiabatic calculations of dynamic polarizabilities and hyperpolarizabilities for low-lying vibrational-rotational states of hydrogen molecular ions

Li-Yan Tang$^{1,3}$, Zong-Chao Yan$^{1,2,3}$, Ting-Yun Shi$^1$, James F. Babb$^3$

1. State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics and Center for Cold Atom Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, P. R. China
2. Department of Physics, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3
3. ITAMP, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA

The static and dynamic electric multipolar polarizabilities and hyperpolarizabilities of H$_2^+$, D$_2^+$, and HD$^+$ ions in the ground states and first excited states are calculated nonrelativistically and nonadiabatically using explicitly correlated Hylleraas basis sets. Comparisons are made with published results. In particular, we make contact with earlier calculations in the Born-Oppenheimer calculation[1]. We find that the static hyperpolarizability for the ground state of HD$^+$ is seven orders of magnitude larger than the corresponding dipole polarizability. For the dipole polarizability of the first excited-state HD$^+$, the high precision of the present method facilitates treatment of a near cancellation between two terms. For applications to laser spectroscopy of trapped ions we find tune-out and magic wavelengths for the HD$^+$ ion in a laser field. In addition, we also calculate the first few leading terms for long-range interactions of a hydrogen molecular ion interacting with a ground-state H, He, and Li atoms.

References
Atomic hyperpolarisabilities and the non-linear optics of atomic gases

Swaantje Grunefeld\textsuperscript{1}, Harry Mulgrew\textsuperscript{1}, Michael Bromley\textsuperscript{1}, Kyle Rollin\textsuperscript{2}, Brandon Rigsbee\textsuperscript{2}, Julia Rossi\textsuperscript{2}, Li-Yan Tang\textsuperscript{3}, Jim Mitroy\textsuperscript{4}, Rifati Handayani\textsuperscript{5}

1. School of Mathematics and Physics, The University of Queensland, Brisbane, Australia
2. Department of Physics, San Diego State University, San Diego, USA
3. Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan, P. R. China
4. School of Engineering, Charles Darwin University, Darwin, Australia
5. Department of Education, University of Jember, Jember, Indonesia

The properties of one and two-electron atoms are calculated numerically using configuration interaction and perturbative methods. We present calculations here for the dynamic hyperpolarizabilities of these atoms, including the excited alkali-metal states spanning up to Rydberg states, e.g. of n = 10. The emphasis here is on low-energy fields of interest in atomic clocks, and high-energy excitations that probe near Rydberg states. The properties of the ground and the excited state hyperpolarizabilities will be discussed, as well as the variance of transition energies and magic wavelengths with hyperpolarizability. A method being developed to approximate the hyperpolarizability contributions from the core electrons will also be introduced. Two forms of the susceptibilities, $\chi_3(\omega, I)$ that describe the non-linear optics of atoms in electric fields, will be presented that describe the variation of the refractive index of an atomic gas in ground or excited states, as well as third-harmonic generation.
Measurement of the 5D Level Polarizability in Laser Cooled Rb Atoms

Stepan Snigirev\textsuperscript{1, 2}, Artem Golovizin\textsuperscript{1, 2, 3}, Dmitry Tregubov\textsuperscript{1, 3}, Sergey Pyatchenkov\textsuperscript{1}, Denis Sukachev\textsuperscript{1, 2, 3}, Alexey Akimov\textsuperscript{1, 2}, Vadim Sorokin\textsuperscript{1, 2}, Nikolay Kolachevsky\textsuperscript{1, 2, 3}

1. P.N. Lebedev Physical Institute, Leninsky Prospekt 53, 119991 Moscow, Russia
2. Russian Quantum Center, ul. Novaya 100, Skolkovo, Moscow region, Russia
3. Moscow Institute of Physics and Technology, 141704 Dolgoprudny, Moscow region, Russia

Polarizabilities of ground and highly excited states of alkali atoms are known quite accurately. Considering intermediate states there are some difficulties both theoretically and experimentally. For example, the polarizabilities of 5S and 5P have been measured long ago with high precision while being in agreement with theory. However, 5D level is challenging. There are several theoretical predictions which differ up to 20\% [1,2]. We managed to measure scalar and tensor polarizabilities with an accuracy of 1\% and 10\% respectively [3].

We used rubidium atoms preliminary cooled and localized in a magneto-optical trap, and formed a cloud at the center of a plane capacitor. Atoms were under the influence of a constant electric field which created the Stark shift of the levels. We measured the shift of the resonant frequency of the transition 5P->5D using the cascade excitation scheme.

References
**An analog of polarization in atom optics: a Raman waveplate to measure the Gouy phase in matter waves**

Justin T. Schultz\(^1,\ 2\), Azure Hansen\(^1,\ 3\), Nicholas P. Bigelow\(^1,\ 2,\ 3\)

1. Center for Coherence and Quantum Optics, University of Rochester, Rochester, NY USA.
2. The Institute of Optics, University of Rochester, Rochester, NY USA.
3. Department of Physics and Astronomy, University of Rochester, Rochester, NY USA.

The field of atom optics has seen the emergence of many analogs of optical components. We extend atom optics to study the analog of optical polarization for the case of a pseudo-spin-1/2 BEC. A two-photon Raman interaction serves as a waveplate for atoms with the retardance controlled by the pulse area and the waveplate angle set by the relative phase of the Raman beams. Using this Raman waveplate in concert with Stern-Gerlach absorption imaging allows us to perform the equivalent of optical polarimetry on a BEC and to obtain the analog of the optical Stokes parameters. This technique allows for the study of atom-optic analogs of optical beams with transverse, spatially varying polarization such as vector vortex and full-Poincare beams. Stokes maps of a full-Bloch BEC can be measured utilizing this technique, and studying the evolution of these maps reveals the Gouy phase for matter waves.

**Atomic matter-wave interferometer on an external atomchip**

Seung Jin Kim\(^1\), Min Seok Kim\(^1\), Seok Tae Gang\(^1\), Jung Bog Kim\(^1\)

1. Department of Physics Education, Korea National University of Education, Chung-Buk 363-791, Korea Republic of

We construct an atomic interferometer using \(^{87}\text{Rb}\) Bose-Einstein condensate trapped on an external atomchip. Our BEC manipulation system has compact size and high-repetition-rate with the help of anodically bonded atomchip on the vacuum cell [1]. A nearly pure condensate is split using RF-induced double well potentials [2]. The trap is turned off allowing the two BECs to interfere in free fall. For varying the RF current frequency and amplitude, we investigate behaviors of the beam-splitter from the observed fringes in the atomic density distribution. We are now working towards more precise control of the atoms.

**References**

A programmable broadband low frequency active vibration isolation system for atom interferometry

Biao Tang¹, ², ³, Lin Zhou¹, ², Zongyuan Xiong¹, ², Jin Wang¹, ², Mingsheng Zhan¹, ²

1. State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China
2. Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China
3. University of Chinese Academy of Sciences, Beijing 100049, China

Vibration isolation at low frequency is important for precision measurement experiments that use atom interferometers (AI). To decrease the vibration noise in an AI, it is crucial to isolate the AI from the environmental vibration noise [1] caused by the retro-reflecting mirror [2, 3] of Raman beams. We designed and demonstrated a compact stable active low frequency vibration isolation system (VIS) for our 10-meter high AI [4], simplified the structure of the active VIS by reducing one actuator, and then built the system using only the basic elements for building a closed loop. With the help of FPGA-based control subsystem, the vibration isolation system performed flexibly and accurately. When the feedback is on, the intrinsic resonance frequency of the system will change from 0.8 Hz to about 0.015 Hz. It can suppress vertical vibrations (0.01-10 Hz) from the background by a factor of 200 with the assistance of a passive vibration isolation platform.

References

Manipulation of atomic velocities with broadband light-pulse atom interferometry

Rachel Gregory¹, Alexander Dunning ², Tim Freegarde¹

1. University of Southampton
2. University of California, Los Angeles

We are investigating the use of light-pulse interferometry techniques for manipulating atomic motion. Interferometer sequences where the output phase is dependent on the initial atomic velocity can be tailored to give cooling forces, and have potential for use in molecular cooling [1]. As a test system, we work on a Doppler-broadened, Zeeman-degenerate sample of Rubidium-85 atoms after release from a MOT, where stimulated Raman pulses form the interferometer beamsplitters and mirrors. These pulses are subject to large amounts of dephasing, which we counteract by adapting NMR-type spin echo and composite pulse techniques. We present a demonstration of cooling of an atomic cloud using interferometric techniques.

References
A milliradian phase resolution Ca atom interferometer with transparent ITO electrodes

Alexander Akentyev\textsuperscript{1, 2}, Taku Kumiya\textsuperscript{1}, Atsuo Morinaga\textsuperscript{1}

1. Tokyo University of Science
2. Moscow Power Engineering Institute

Recently, the Röntogen phase (He-McKellar-Wilkens phase) was measured using a large Mach-Zehnder atom interferometer by Gillot et al. \cite{1}, where a large Stark phase shift results in reductions in visibility. We have developed an atom interferometer with milliradian phase resolution using a sub-Hz linewidth diode laser \cite{2} and free from a large Stark phase shift using the transparent ITO electrodes with anti-reflection coating. The Ramsey-Bordé atom interferometer was composed of the \textsuperscript{3}P\textsubscript{1} and \textsuperscript{1}S\textsubscript{0} states of Ca atoms which were excited by two pairs of the copropagating parallel laser beams with equal distances. The first pair of beams were incident on the first electrode and the other pair of beams were incident on the second electrode with the same strength but opposite direction of the electric field, so that the Stark phase shifts can be cancelled out. The phase shifts under the electric field and the magnetic field are investigated.

References

\cite{1} S. Lepoutre et al., Phys. Rev. Lett. 109, 120404 (2012)
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Large Momentum Transfer and Faster Signal Scalings in Acceleration-Sensitive Atom Interferometry

Gordon McDonald\textsuperscript{1}, Carlos Kuhn\textsuperscript{1}, Shayne Bennetts\textsuperscript{1}, John Debs\textsuperscript{1}, Kyle Hardman\textsuperscript{1}, John Close\textsuperscript{1}, Nicholas Robins\textsuperscript{1}

\textsuperscript{1} Quantum Sensors Lab, Department of Quantum Science, Research School of Physics and Engineering, Australian National University, Canberra, 0200, Australia

We have demonstrated an acceleration-sensitive atom interferometer configuration with 80 photon recoils of momentum separation between the two arms of the interferometer \cite{1} (also at arXiv:1307.0268). This is the largest momentum splitting yet achieved while maintaining a measurable interferometric signal. We construct the interferometer horizontally, through the use of a horizontal optical waveguide. This interferometer configuration is based upon a combination of multiple 10-photon-recoil Bragg splitting pulses combined with momentum-state-selective acceleration (of up to 60 photon recoils) in an optical Bloch lattice.

Using this technique we have demonstrated an increased scaling law of interferometric signal with time \cite{2} (also at arXiv:1311.2143). A standard Ramsey-Bordé configuration has a signal proportional to the interferometer time, \(T\); while the standard Mach-Zehnder configuration has a signal proportional to \(T^2\). We demonstrate a configuration in which the signal scales faster than \(T^3\), and suggest extension to even higher powers of \(T\). This technique should allow higher sensitivity for the same interferometer time, or the same sensitivity in a shorter time, allowing measurements of more quickly changing accelerations.

References
Progress towards in-beam hyperfine spectroscopy of antihydrogen

Eberhard Widmann\textsuperscript{1}, Peter Caradonna\textsuperscript{1}, Martin Diermaier\textsuperscript{1}, Nazli Dilaver\textsuperscript{1}, Bernadette Kolbinger\textsuperscript{1}, Chloe Malbrunot\textsuperscript{1,2}, Oswald Massizcek\textsuperscript{1}, Clemens Sauerzopf\textsuperscript{1}, Martin C. Simon\textsuperscript{1}, Michael Wolf\textsuperscript{1}, Johann Zmeskal\textsuperscript{1}

\textsuperscript{1}. Stefan Meyer Institute for Subatomic Physics, Boltzmanngasse3, 1090 Vienna, Austria
\textsuperscript{2}. CERN, Geneva, Switzerland

Antihydrogen is the simplest atom consisting purely of antimatter. Its matter counterpart, hydrogen, is one of the best studied atomic systems in physics. Thus comparing the spectra of hydrogen and antihydrogen offers some of the most sensitive tests of matter-antimatter symmetry. The ASACUSA collaboration is pursuing an experiment to measure the ground-state hyperfine splitting of antihydrogen in a polarized beam [1,2], a quantity which was measured in hydrogen in a beam to a relative precision of $4 \times 10^{-8}$ [3] and in a maser to better than $10^{-12}$ [5,6].

After recently reporting the first observation of a beam of antihydrogen atoms 2.7 m downstream of the formation region in a field-free environment [4], preparations are under way to finalize the atomic resonance beam apparatus to perform a hyperfine measurement. During the shutdown of CERN, a source of cold polarized hydrogen atoms was built and experiments are under way to characterize the apparatus with a hydrogen beam of similar properties as compared to the expected antihydrogen beam. First scans of the hyperfine structure of hydrogen showing encouraging results for the achievable precision in a measurement with antihydrogen will be reported.

References
ALPHA-2: an upgraded apparatus for physics with trapped antihydrogen

Stefan Eriksson, The ALPHA-collaboration

1. Department of Physics, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP, UK
2. CERN, CH-1211 Geneve 23, Switzerland

Antihydrogen offers a unique way to test matter/antimatter symmetry. Antihydrogen can reproducibly be synthesised and trapped in the laboratory for extended periods of time [1, 2] offering an opportunity to study the properties of antimatter at high precision. New techniques to study antihydrogen have emerged; the ALPHA collaboration at CERN can now interrogate the bound state energy structure with resonant microwaves [3] and determine the gravitational mass to inertial mass ratio [4]. The results are not yet sensitive enough to draw conclusions on matter/antimatter symmetry but the recent progress shows that experiments with trapped antihydrogen are possible and the collaboration is firmly en-route towards precision measurements. The ALPHA-collaboration has upgraded the trapping apparatus improving access for both laser beams and microwave radiation. We present the upgraded apparatus in detail.

References
Positron storage for the production of an antihydrogen beam

D.J. Murtagh$^1$, S. Ulmer$^2$, S. Van Gorp$^1$, K. Michishio$^3$, H. Nagahama$^4$, S. Sakurai$^5$, H. Higaki$^5$, Y. Kanai$^1$, Y. Yamazaki$^{1,4}$

1. Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan
2. Ulmer Initiative Research Unit, RIKEN, Saitama 351-0198, Japan
3. Department of Physics, Tokyo University of Science, Tokyo 162-8601, Japan
4. Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan
5. Graduate School of Advanced Sciences of Matter, Hiroshima University, Hiroshima 739-8530, Japan

Since the recent publication of the first observation of an antihydrogen beam by the ASACUSA-Cusp collaboration [1], work has been undertaken to improve the experimental setup to produce a more intense beam, and hence realise the physics goal of the experiment - Rabi-like beam spectroscopy of antihydrogen. Of crucial importance to these efforts is the production and storage of a dense positron plasma. During the long shutdown at CERN work has been undertaken to improve the positron accumulation apparatus. The positron trapping rate has been increased by an order of magnitude from $7 \times 10^4$ /s [1] to $7 \times 10^5$ /s. This has been achieved by improving a number of different experimental conditions, including increasing the trap magnetic field from low (0.3 T) to high (1 T). In this poster, the ASACUSA-cusp collaboration positron accumulation apparatus and present results will be discussed.

References
Production of a cold antihydrogen beam with a cusp trap


1. Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan
2. Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan
3. Ulmer Initiative Research Unit, RIKEN, Saitama 351-0198, Japan
4. Stefan-Meyer-Institut fuer Subatomare Physik, Oesterreichische Akademie der Wissenschaften, Wien 1090, Austria
5. CERN, Geneva 1211, Switzerland
6. Dipartimento di Ingegneria dell'Informazione, Universita di Brescia, Brescia 25133, Italy
7. Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Brescia, Brescia 25133, Italy
8. Department of Physics, Tokyo University of Science, Tokyo 162-8601, Japan
9. Graduate School of Advanced Sciences of Matter, Hiroshima University, Hiroshima 739-8530, Japan

Antihydrogen is the simplest atomic system to perform precision measurements on the properties of antimatter. Comparing the ground-state hyperfine transition frequencies of hydrogen and antihydrogen is one of the most sensitive direct tests of CPT symmetry. Towards this goal the ASACUSA collaboration had developed an antihydrogen beam apparatus that can be used for Rabi-like in-flight spectroscopy measurements. The production of antiatoms is performed in an anti-Helmholtz type magnetic configuration (cusp), which allows spin-dependent focusing and formation of a polarised beam. During mixing of antiprotons and positrons in the cusp field a total of 80 antihydrogen atoms have been successfully detected 2.7 meters away from the source, where residual magnetic fields are negligible. After correcting for detection efficiency the beam count rate for antiatoms with n<43 principal quantum number was 40 mHz [1]. This result opens a new window to direct tests of fundamental symmetries in the Standard Model of elementary particle physics.

References
Hyperfine structure and relativistic corrections to ro-vibrational energy levels of the D$_2^+$ ion

Pei-Pei Zhang$^1$, Zhen-Xiang Zhong$^1$, Zong-Chao Yan$^2$

1. Division of Theoretical and Interdisciplinary Research, State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China

2. Department of Physics, University of New Brunswick, Fredericton, New Brunswick, E3B 5A3, Canada

Provided high-resolution laser spectroscopy is feasible for the D$_2^+$ ion, together with high precision calculations of relativistic and quantum electrodynamical corrections, it is possible to derive an improved value of the deuteron-electron mass ratio and extract properties of the deuteron [1]. Although hydrogen molecular ion isotopes of H$_2^+$ and HD$^+$ have been studied intensively both theoretically and experimentally [2], there is scarce work on the D$_2^+$ ion. In this paper, we will present a systematic calculation of ro-vibrational energy levels and hyperfine structure of the D$_2^+$ ion, including the leading-order relativistic and QED corrections, for the state of $(v, L)$, where $v = 0-4, L = 0-4$.

References

μTest of the change of $m_p/m_e$ using laser cooled and optically trapped $^{40}$CaH

Masatoshi Kajita$^1$, Geetha Gopakumar$^2$, Minori Abe$^2$, Masahiko Hada$^2$

1. National Institute of Information and Communications Technology
2. Tokyo Metropolitan University

We propose to test the variation in the proton-to-electron mass ratio via the precise measurement of the $^{40}$CaH $X^2\Sigma(v,N,F,M) = (0,0,1,+/-1) - (1,0,1,+/-1)$ transition frequency (37.8 THz) with the uncertainty of the order of $10^{-17}$. $^{40}$CaH molecules are produced by laser ablation on $^{40}$CaH$_2$ crystal and buffer-gas cooled. Doyle group succeeded to get a $^{40}$CaH molecular beam with the kinetic energy of 4 K with $10^8$ molecules/pulse [1]. The kinetic energy can be reduced by laser-cooling (Doppler cooling + Polarizatino gradient cooling) [2,3]. Molecules with kinetic energy lower than 10 μK are trapped in a 3D optical lattice. The trap laser frequency is tuned to frequency, where the Stark shift in the transition frequency is eliminated (magic frequency). The magic frequencies are estimated to be 378.43 THz and 465.14 THz, where the Stark shift with the intensity yielding the potential depth of 10μK is less than $10^{-16}$ when the trap laser frequency is detuned from the magic frequencies by 1 MHz.

References
Test of $m_p/m_e$ variation via measurement of $N_2^+$ vibrational transition frequencies

Masatoshi Kajita$^1$, Geetha Gopakumar$^2$, Minori Abe$^2$, Masahiko Hada$^2$, Matthias Keller$^3$

1. National Institute of Information and Communications Technology
2. Tokyo Metropolitan University
3. Sussex University

We propose to test the variation in the proton-to-electron mass ratio by measuring the $X^2\Sigma_g(v,N,F,M) = (0,0,1/2,\pm 1/2) - (1,0,1/2,\pm 1/2)$ transition frequencies of $N_2^+$ ($I = 0$) molecular ion $[1]$. $N_2^+$ molecular ions are trapped in a linear electrode after the state selective resonance-enhanced multiphoton ionization of $N_2$ molecules, and sympathetically cooled with laser cooled ions $[2]$. As there is no E1 transition between different vibrational-rotational states in the $X^2\Sigma_g$ state, the thermalization by blackbody radiation is inhibited. With this transition, the Zeeman and electric quadrupole shifts are zero. The Stark shift induced by the trap electric field is less than $10^{-19}/(V/cm)^2$, therefore, the measurement can be performed also with a Coulomb crystal with a broadening of 10 μm in the radial direction. This transition is observed by Raman transition eliminating the Stark shift by employing lasers with "magic" wavelength. Therefore, measurement with the uncertainty of the order of $10^{-17}$ is possible using a simple experimental setup (employment of cryogenic chamber and formation of a string crystal are not necessary).

References


Test of Einstein Equivalence Principle with bosonic and fermionic quantum matter: Search for spin-gravity coupling effects

Marco G. Tarallo$^1$, $^2$, Tommaso Mazzoni$^1$, Nicola Poli$^1$, Denis V. Sutyrin$^1$, Xian Zhang$^1$, Guglielmo M. Tino$^1$

1. Dipartimento di Fisica e Astronomia and LENS–Università di Firenze, INFN–Sezione di Firenze, Via Sansone 1, 50019 Sesto Fiorentino, Italy
2. Department of Physics, Columbia University, 538 West 120th Street, New York, New York 10027-5255, USA

We report on a conceptually new test of the equivalence principle performed by measuring the acceleration in Earth's gravity field of two isotopes of strontium atoms, the bosonic $^{88}$Sr isotope which has no spin vs the fermionic $^{87}$Sr isotope which has a half-integer spin. The effect of gravity upon the two atomic species has been probed by means of a precision differential measurement of the Bloch frequency for the two atomic matter waves in a vertical optical lattice, improving the short-term sensitivity of the atomic gravimeter of a factor 16. Both the scalar and spin-gravity universality of free-fall were tested with a relative precision of $10^{-7}$. 
Species-Selective Lattice Launch for High-Precision Atom Interferometry

Raja Chamakhi\textsuperscript{1, 2}, Holger Ahlers\textsuperscript{3}, Naceur Gaaloul\textsuperscript{3}, Ernst Rasel\textsuperscript{3}, Mourad Telmini\textsuperscript{1}

1. LSAMA Department of Physics, Faculty of Sciences of Tunis, University of Tunis El Manar, 2092 Tunis, Tunisia
2. National Centre for Nuclear Science and Technology, Sidi Thabet Technopark, 2020 Tunis, Tunisia
3. Institut für Quantenoptik, Welfengarten 1, Gottfried Wilhelm Leibniz Universität, 30167 Hannover, Germany

We propose a new technique \cite{1} to be applied in atomic fountains to test the Einstein’s Equivalence Principle (EEP) with dual species in the condensed phase \cite{2-5}. So far, these fountains do not allow for a selective acceleration of two different species of atoms thus limiting the performances of an EEP test \cite{6}.

With our method we propose to use two laser wavelengths, each beam interacting with only one atom species. By this way, we achieve a selective control of the velocity of each isotope, leading to unprecedented precision of a quantum EEP test.

At this point and having the physical recipe and numerical tools in hand, we are summing up this method for the realistic case of Rb/K mixtures with state-of-the-art technology lasers.

References
Testing General Relativity in a terrestrial lab through laser gyroscopes

Nicolò Beverini¹, ², Jacopo Belfi², Massimo Calamai¹, ², Giorgio Carelli¹, ², Davide Cuccato³, ⁴, Angela Di Virgilio², Enrico Maccioni¹, ², Antonello Ortolan⁴, Alberto Porzio⁵, Rosa Santagata², ⁶, Angelo Tartaglia⁷

¹. University of Pisa, Department of Physics, Italy
². INFN, Sezione di Pisa, Italy
³. Department of Information Engineering, Università di Padova, Italy
⁴. INFN, Laboratori di Legnaro, Italy
⁵. CNR-SPIN, and INFN, sezione di Napoli, Italy
⁶. Dipartimento di Fisica, Università di Siena, Italy
⁷. Politecnico of Torino and INFN, Torino, Italy

GINGER (Gyroscopes IN GEneral Relativity) is an INFN project[1] for measuring in a ground-based observatory the Lense-Thirring effect (the inertial frame dragging, foreseen by General Relativity, induced by the proper rotation of a massive source). It will consist in a structure of three laser gyroscopes mutually orthogonal with about 6m of side, located in a deep underground location, possibly the GranSasso INFN laboratory. The triaxial structure will provide full determination of the laboratory frame angular velocity to be compared with the Earth rotation rate in the fixed stars frame given by IERS through VLBI.

Large-size gyrolasers have already reach very high sensitivity, allowing relevant geodetic measurements[2]. The accuracy required for LT effect measurement is better than $10^{-14}$ rad/s: Earth angular velocity must be measured at $10^{-9}$ accuracy, with one order of magnitude improvement on actual level. We will present the main issues and the chosen strategy for achieving this goal.

References
Magic wavelengths measurement via observation of light shift on $^{40}$Ca$^+$ optical frequency standard

Kelin Gao

1. Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences

The ratio of the oscillator strengths is one of the most important indexes in atomic transitions, which can be calculated via the measurement of the magic wavelengths, which have been predicted theoretically and measured experimentally in neutral atomic systems. Magic wavelengths also exist in ion systems. A scheme of measuring the magic wavelengths is introduced via observation of light shift in $^{40}$Ca$^+$ optical frequency standard; it is the first time realized in ion system. By this method, two magic wavelengths are measured with high precision, and the values are $\lambda_{|m|=1/2}=395.7992(7)$ nm and $\lambda_{|m|=3/2}=395.7990(7)$ nm, which is agree with the theory within a fractional uncertainty of $<4\times10^{-6}$. Based on the two magic wavelengths measured, the ratio of the oscillator strengths on $4S_{1/2}-4P_{1/2}$ and $4S_{1/2}-4P_{3/2}$ transitions is calculated to be 2.009(4), with a fractional uncertainty of $\sim2.0\times10^{-3}$.

References

Determination of the magic wavelength for the $^1S_0$ - $^3P_0$ transition in magnesium 24

Dominika Fim, André Kulosa, Steffen Rühmann, Klaus Zipfel, Steffen Sauer, Birte Lampmann, Wolfgang Ertmer, Ernst M. Rasel

1. Institut fuer Quantenoptik, Leibniz Universitaet Hannover, Hannover, Germany

We report on the experimental determination of the magic wavelength for the spin-forbidden clock transition in magnesium 24. The knowledge of this particular wavelength, where the differential AC Stark shift of the involved clock states vanish, is mandatory for clock operation with a high accuracy.

A continuous loading scheme transfers atoms into a dipole trap opening a loss channel to the $^3P_0$ state, where the coldest atoms get trapped. This is necessary due to ionization of the $^3D$ states by the magic light and the lack of sud-Doppler cooling techniques. $10^4$ atoms are further transferred to the optical lattice.

Evaluating the differential light shift of the carrier transition, we could determine the magic wavelength to $468.38\pm0.35$ nm. Further investigations will minimize this uncertainty.
Improving the stability of an atomic clock

Marco Schioppo\textsuperscript{1,2}, Nathaniel B. Phillips\textsuperscript{1}, Kyle Beloy\textsuperscript{1}, Nathan Hinkley\textsuperscript{1,2}, Jeffrey A. Sherman\textsuperscript{1}, Chris W. Oates\textsuperscript{1}, Andrew D. Ludlow\textsuperscript{1}

1. National Institute of Standards and Technology (NIST), Boulder, CO, USA
2. Department of Physics, University of Colorado, Boulder, CO, USA

The stability of an atomic clock sets the timing precision it can achieve, and further influences the pursuit of higher accuracy. Here we discuss efforts and strategies towards the goal of reaching $1 \times 10^{-18}$ instability in $<1000$ seconds averaging-time. An important stability limit, the Dick effect, stems from the sequential nature of the measurement procedure in which the interrogation-time is only a fraction of the total cycle-time. Synchronous interrogation of two atomic systems permits common-mode rejection of the Dick effect in comparative measurements, and we demonstrated measurement improvements from this technique. By employing an interleaved, anti-synchronized interrogation of two atomic systems, we can achieve zero-dead-time operation, which highly suppresses the aliasing problem at the heart of the Dick effect. Furthermore, efforts to improve the frequency stability of the cavity-stabilized probe laser beyond the state-of-the-art are described, as well as operation with large atom number for reducing the quantum projection noise.

Reducing the uncertainty of blackbody radiation shift in a strontium optical clock

Ali Al-masoudi, Stephan Falke, Sören Dörscher, Stefan Vogt, Sebastian Häfner, Uwe Sterr, Christian Lisdat

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

Optical clocks have demonstrated remarkable performance in terms of stability and accuracy and therefore have a large range of applications in fundamental physics and metrology. We are operating an optical clock based on strontium atoms trapped in an optical lattice [1]. The uncertainty of our $^{87}$Sr strontium lattice clock is $3 \times 10^{-17}$, where the dominating contribution is due to the uncertainty of the blackbody radiation (BBR), The BBR field needs to be known more accurately to reduce this uncertainty contribution: Currently we are working on the way to interrogate $^{87}$Sr atoms in an environment with well controlled temperature, since a well controlled temperature produces a well characterized BBR field that allows together with an accurately known atomic reaction to the BBR field [2] for a high accuracy correction of the BBR shift. We expect an uncertainty contribution from the BBR shift of about $5 \times 10^{-18}$.

This work is supported by RTG 1729, QUEST and the European Metrology Research Programme (EMRP) in ITOC and QESOCAS. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

References
Precise characterization of the blackbody radiation environment in an optical lattice clock

Kyle Beloy, Nathan Hinkley, Jeff Sherman, Nathaniel B. Phillips, Marco Schioppo, Chris W. Oates, Andrew Ludlow

1. National Institute of Standards and Technology, Boulder, CO, USA
2. University of Colorado, Boulder, CO, USA

The Stark shift caused by blackbody radiation (BBR) is a key factor limiting the performance of many atomic frequency standards, due in part to the difficulty in precisely characterizing the BBR environment bathing the atoms. Here we describe the implementation of an in-vacuum radiation shield that furnishes a uniform, well-characterized BBR environment for the atoms in an optical lattice clock. Under normal (room-temperature) operation, this shield enables specification of the BBR shift to better than 1 ppt for our Yb lattice clock, corresponding to an uncertainty contribution of $1 \times 10^{-18}$ in fractional frequency units. Further operation of the shield over a range of elevated temperatures demonstrates consistency between our evaluated BBR environment and the expected atomic response.

The SOC2 transportable $^{171}$Yb lattice clock

Axel Goerlitz, Gregor Mura, Tobias Franzen, Charbel Abou-Jaoudeh, Heiko Luckmann, Ingo Ernsting, Alexander Nevesky, Stephan Schiller

1. University of Duesseldorf

Optical lattice clocks based on elements with two valence electrons like Sr, Hg, Mg and Yb are strong competitors in the quest for next generation time and frequency standards. Recently, a stability and accuracy in the $10^{-18}$ range has been reported for lattice clocks using Yb [1] and Sr [2] for stationary setups.

In the framework of the SOC2 project [3], we are developing a transportable Yb lattice clock demonstrator, since the development of transportable optical lattice clocks is desirable for both performance evaluation and applications, e.g. in a microgravity environment. To ensure transportability, our setup is based entirely on diode and fiber lasers and features an intra-vacuum enhancement resonator to allow the formation of a large volume lattice using moderate laser power. We present a characterization of our clock setup, as well as our plans for a transport of the apparatus from the University of Duesseldorf to INRIM in Torino.

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 263500.

References
An ultra-low frequency-noise laser based on a 48 cm long ULE cavity for a Sr lattice clock

S. Häfner¹, S. Vogt¹, A. Al-Masoudi¹, C. Grebing¹, M. Merimaa², Th. Legero¹, Ch. Lisdat¹, U. Sterr¹

¹. Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
². Center for Metrology and Accreditation (MIKES); P.O Box 9; FI-02151 Espoo, Finland

Ultra-stable lasers are essential instruments to interrogate narrow atomic transitions, e.g. in optical atomic clocks. The stability of ultra-stable lasers is obtained from the length stability of an external reference cavity, which is fundamentally limited by the Brownian thermal noise of the material, especially of the mirrors.

We have designed a 48 cm long cavity made of ultra low expansion (ULE) glass. In order not to be limited through length fluctuations induced by vibration acceleration a special balanced mount was implemented. Using three heat shields and precision temperature controls we have obtained a thermal time constant of about 10 days and a temperature variation measured close to the cavity of 2 µK in 1000 s. From a comparison with the Sr lattice clock [1] we have observed a laser instability of $7 \times 10^{-17}$ at 300 s averaging time. With this laser the clock instability was reduced to $4 \times 10^{-16} (\tau/s)^{-1/2}$.

References
Dual species intercombination MOT of $^{171}$Yb and $^{87}$Sr: Toward a dual optical lattice clock

Daisuke Akamatsu$^1$, Masami Yasuda$^1$, Hajime Inaba$^1$, Kazumono Hosaka$^1$, Sho Okubo$^1$, Takehiko Tanabe$^1$, Atsushi Onae$^1$, Feng-Lei Hong$^1$

1. National Metrology Institute of Japan

An optical lattice clock is one of the promising candidates for the redefinition of the second. Frequency comparisons of same optical lattice clocks have been carried out and their reproducibilities have been confirmed at the $10^{-17}$ level [1,2]. Recently, a comparison of optical lattice clocks with different species has been performed to determine the frequency ratio of the clock transitions [3]. In these experiments, the uncertainty of the temperature of the environment dominates the uncertainty of the measurement results.

Our aim is to demonstrate two optical lattice clocks of $^{171}$Yb and $^{87}$Sr in the same chamber (dual optical lattice clock). Since the trapped atoms are surrounded by the same blackbody radiation (BBR), the frequency shift due to the BBR would be partially cancelled, resulting in a smaller uncertainty in the frequency ratio measurement. The recent demonstration of dual species intercombination MOT of $^{171}$Yb and $^{87}$Sr will be presented.

References
Measurement of the clock-transition spectrum of the ultracold ytterbium atoms

Xinye Xu\textsuperscript{1}, Xiaohang Zhang\textsuperscript{1}, Ning Chen\textsuperscript{1}, Min Zhou\textsuperscript{1}, Su Fang\textsuperscript{1}, Yuan Yao\textsuperscript{1}, Longsheng Ma\textsuperscript{1}, Qi Gao\textsuperscript{1}, Chengyin Han\textsuperscript{1}, Yiling Xu\textsuperscript{1}

\textsuperscript{1}. State Key Laboratory of Precision Spectroscopy and Department of Physics, East China Normal University, Shanghai 200062, China

We have done the experiments on developing the ytterbium optical clock. By two-stage laser cooling, the $^{171}$Yb atoms are cooled down to 10 $\mu$K. Then they are loaded into an optical lattice with the wavelength of 759 nm. Furthermore the lifetime and temperature of atoms in the optical lattice are measured. We have observed the $^{1}S_{0}^{1/2}$-$^{3}P_{0}^{1/2}$ clock-transition spectra of the ultracold $^{171}$Yb atoms in the optical lattice by using the ultranarrow-linewidth 578-nm laser. First we find the resonant frequency of the clock-transition $^{1}S_{0}^{1/2}$-$^{3}P_{0}^{1/2}$ by measuring the ground-state population as a function of the frequency of the 578-nm laser; then we precisely measure the clock-transition spectra by using the normalization method with help of the pumping lasers, the 649-nm laser for the transition $^{3}P_{0}^{1/2}$-$^{3}S_{1}^{1/2}$ and the 770-nm laser for the transition $^{3}P_{2}^{3/2}$-$^{3}S_{1}^{1/2}$. At present the linewidth of the clock-transition spectrum of the $^{171}$Yb atoms is about 16 Hz for the 60-ms interrogating time.

Comparison between a strontium optical lattice clock with primary and secondary frequency standards

Jean-Luc Robyr\textsuperscript{1}, Chunyan Shi\textsuperscript{1}, Ulrich Eismann\textsuperscript{1}, Jocelyne Guéna\textsuperscript{1}, Peter Rosenbusch\textsuperscript{1}, Michel Abgrall\textsuperscript{1}, Daniele Rovera\textsuperscript{1}, Sébastien Bize\textsuperscript{1}, Philippe Laurent\textsuperscript{1}, Yann Lecoq\textsuperscript{1}, Rodolphe Le Targat\textsuperscript{1}, Jérôme Lodewyck\textsuperscript{1}

\textsuperscript{1}. LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, Paris, France

The LNE-SYRTE atomic clock ensemble allows high accuracy frequency comparisons between the microwave (Cs, Rb) and the optical (Sr, Hg) frequency domains with an overall uncertainty of a few $10^{-16}$ [1]. In order to highlight the Sr optical clock potential to realize a future "optical second", we have compared the Sr clock with Cs and Rb frequency standards in several measurement campaigns that will also contribute to further constraint an hypothetical drift of the fundamental constants. The result of these measurements will be presented. In parallel, we will report on the efforts to improve the LNE-SYRTE Sr optical lattice clocks performances, by reducing the uncertainty budget due to blackbody radiation frequency shift, by reaching better stability with cavity based nondestructive detection [2], and by actively stabilising the phase dissemination of the ultra stable "clock" laser.

References

Non-destructive imaging and feedback stabilized production of cold atomic clouds

Miroslav Gajdacz¹, Poul L. Pedersen¹, Andrew J. Hilliard¹, Jan Arlt¹, Jacob F. Sherson¹

1. Institut for Fysik og Astronomi, Aarhus Universitet, Ny Munkegade 120, 8000 Aarhus C, Denmark.

Reliable production of cold atomic clouds with well-defined properties is a notoriously difficult task. Variations in the final atom number and temperature arise mainly due to unpredictable fluctuations in the experimental sequence. Non-destructive measurements of the ensemble properties within the sequence allow for an adjustment of the cooling procedure to obtain the desired outcome. Our scheme utilizes an imaging technique based on Faraday rotation combined with on-line digital image evaluation and feedback to the evaporation sequence. We demonstrate sub-percent run to run stability of the final atom number obtained by a single point feedback and discuss the limitations of this approach. A weak-gain multiple point feedback can be applied to counteract repeated external disturbances. In addition, it is investigated if the formation of a Bose-Einstein condensate can be stabilized by this feedback mechanism.

References
Dispersive probing as a tool for monitoring dynamical processes in ultracold gases

Amita B. Deb¹, Bianca J. Sawyer¹, Niels Kjaergaard¹

1. Jack Dodd Center for Quantum Technologies, Department of Physics, University of Otago, New Zealand

We report on heterodyne detection for tracking the evolution of the density and quantum state populations of ultracold atomic samples via dispersive light-matter interactions. As an example, the process of forced evaporative cooling was followed non-destructively in real time. Using the information gained from such dispersive interrogations the number fluctuations in the resultant sample can be conditionally reduced [1]. Extending on our scheme, we have monitored the coherent spin dynamics in a prolate sample evolving in magnetic field gradient under the action of a near-resonant Rabi-drive [2]. From the recorded heterodyne signal, gradiometry with a bandwidth in the kilohertz domain was performed in a single-shot measurement. We present our ongoing work on a novel separate-paths multi-heterodyne dispersive probing scheme aimed at non-destructive tracking of atom-molecule coherence near Feshbach resonances [3], and simultaneously probing multiple quantum states.

References

Compact semiconductor laser modules for precision quantum optical experiments in space

Wojciech Lewoczko-Adamczyk¹,², Ahmad I. Bawamia¹, Mandy Krueger¹, Christian Kuerbis¹, Martin Heyne¹, Andreas Wicht¹, Goetz Erbert¹, Achim Peters¹,²

1. Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenstechnik, Berlin, Germany
2. Humboldt-Universitaet zu Berlin, Germany

We present a novel technology for assembling ultra-stable, space qualified semiconductor laser systems. Electronic and optical components of our laser modules are micro-integrated on an aluminium nitride (AlN) ceramic plate with a footprint of 30x80mm² only. To meet the requirements for operation in space the laser is hermetically sealed in a robust metal housing. The AlN body can be equipped with two arbitrary laser chips, a chip-based phase modulator, an optical grating, and two optical fiber ports. This allows for realization of diverse hybrid compact laser systems like for instance a high power, narrow linewidth Extended Cavity Diode Laser (ECDL) followed by a Power Amplifier (PA). This combination is suitable for experiments in quantum optics including laser cooling, optical trapping and atom interferometry.

Moreover, we show that our technology platform is capable of housing ultra-narrow-linewidth lasers enhanced by an optical cavity, frequency doubled lasers as well as compact spectroscopy units.
Subwavelength alteration of one-dimensional optical lattices using radiofrequency-induced adiabatic potentials

Nathan Lundblad

1. Bates College, Lewiston, ME 04240

Traditional optical lattices are limited in length scale to approximately half a wavelength of the lattice laser; the ability to tailor a lattice’s periodicity, band structure, and Wannier functions would be a significant aid in using optical lattices to explore analogous solid-state physics. One pathway to lattice modification is the use of radiofrequency dressing to create adiabatic potentials of novel geometry from “bare” spin-dependent lattices of traditional geometry. We present measurements made on a one-dimensional radiofrequency-dressed optical lattice in the new regime where the dressed lattice is both deeper than previously achieved and longer-lived. Momentum distributions, loss rates, and dressed-state spin populations are explored. The bare lattices are sufficiently deep and the rf coupling sufficiently strong such that the adiabatic potentials could potentially be useful for experiments exploring novel optical lattice geometries.

Scalable 2D array of dipole traps formed by pinhole diffraction for neutral atom quantum computing

Katharina Gillen-Christandl, Glen Gillen, Sanjay Khatri, Ian Powell, Jason Schray, Taylor Shannon

1. California Polytechnic State University, San Luis Obispo

To build a scalable neutral atom quantum computer, we propose trapping atoms in the dipole traps formed by diffraction at a two-dimensional array of pinholes. We have computed the properties of traps formed by diffraction of laser light at a pinhole for realistic laser parameters [1]. Using two circularly polarized laser beams incident at an angle, atoms can be brought together and apart controllably by exploiting the light polarization dependence of the traps [2]. The diffraction pattern can be projected into a vacuum chamber by a single lens, resulting in different trap sizes and aspect ratios depending on the lens placement [3]. We are exploring changes to the diffraction pattern for large incident laser angles that limit the range of motion of our traps. We will present comparisons of our computational results with direct intensity measurements, and our progress towards building an experimental setup to load atoms into these traps.

References
Design of optical Talbot focal point array for neutral atom quantum computing

Hyosub Kim, Wooujun Lee, Hangyeol Lee, Jaewook Ahn
1. Dept. of Phys., KAIST, South Korea

As a new platform for quantum computation and quantum simulation, we consider atoms regularly arranged in space via optical Talbot effect. We design an atom array, formed as a periodic self-image of light transmitted through a periodic structure, to satisfy both the individual qubit control and entanglement conditions (i.e., \( \lambda_{\text{Laser}} < d < 10 \lambda_{\text{Laser}} \)). For this, we have fabricated a two-dimensional grating with a 50x50 micro-hole array on a chromium sputtered glass substrate, and tested its performance by quantum-dot sheet fluorescence tomography. The resulting Talbot carpet image in three dimension exhibits that the period of five-micrometer and lateral focal point size of less than 1 micrometer (i.e., \( \Delta x \sim \lambda_{\text{Laser}} \)) are achieved. We plan to capture cold rubidium single atoms in an off-resonant dipole trap array of triangular lattice structure.

Bose-Einstein Condensation in a Periodic Magnetic Lattice

Yibo Wang1, Prince Surendran1, Smitha Jose1, Ivan Herrera1, Leszek Krzemien2, Shannon Whitlock 3, Russell McLean1, Andrei Sidorov1, Peter Hannaford1

1. Centre for Quantum and Optical Science, Swinburne University of Technology, Melbourne, Australia 3122
2. Jerzy Haber Institute of Catalysis & Surface Chemistry, Polish Academy of Sciences, 30-239 Krakow, Poland
3. Physikalisches Institut, Universitätat Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

We report the realization of a periodic array of Bose-Einstein condensates of \(^{87}\text{Rb} F=1\) atoms trapped in a 1D 10 \( \mu \text{m} \)-period magnetic lattice created by a patterned magnetic film on an atom chip [1]. Clear signatures for the onset of BEC in multiple sites of the magnetic lattice is provided by in-situ site-resolved radiofrequency spectroscopy, in which the spectra reveal pronounced bimodal distributions consisting of a narrow component characteristic of a BEC together with a broad thermal cloud component. The realization of a periodic array of BECs in a magnetic lattice represents a significant step toward the implementation of magnetic lattices for quantum simulation of many-body condensed matter phenomena in lattices of complex geometry such as triangular, honeycomb, Kagome and super-lattices.

References

Generalized Thermodynamic Properties

Jesus Morales, Jose Juan Peña

1. Universidad Autónoma Metropolitana - Azcapotzalco, Ciencias Básicas, Area de Física Atómica
   Molecular Aplicada, San Pablo 180, 02200 México, D. F.

In a previous work [1], we have proposed a Schrödinger-like thermodynamic equation where
the role played by the quantum wavefunctions and Witten superpotential are carried out by
the statistical partition functions $Z(T)$ and internal energy $U(T)$, respectively. In this work, we
propose a non linear differential equation, of Riccati type, where the variable is the standard
$Z(T)$ that is used as particular solution to obtain its generalized $Z_g(T)$; from there, any other
thermodynamic property is straightforwardly improved. As an useful application of $Z_g(T)$, the
study of the generalized thermodynamic properties $U_g(T)$, heat capacity $C_g(T)$ and entropy $S_g$
$(T)$, associated to the model of ideal monatomic gas in one, two and three dimensions, is shown.
Beyond this example, due that the proposal is general this can be used to generalize other
thermodynamic statistical models as well as to obtain new partition functions that can be used
advantageously in modeling thermodynamic applications.

References

Supersymmetry, shape invariance and the
hypergeometric equation

Pushpa1, Ashok Das2

1. Instituto de Física, Universidade de São Paulo, 05508-090, São Paulo, SP, Brazil
2. Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627-0171, USA

In quantum mechanics, supersymmetry relates a pair of Hamiltonians which are almost
isospectral. Shape invariance arises in a supersymmetric system with special forms of the
potential which remain form invariant as one goes from one Hamiltonian to its supersymmetric
partner. We have shown that the solubility of the hypergeometric equation can be understood
as an underlying supersymmetry and shape invariance of the differential equation. The study of
the hypergeometric equation is important because the hypergeometric function contains all of
the orthogonal polynomials for special values of the three parameters that it depends on. Since
each of the orthogonal polynomials defines a complete basis in which the wave function of any
quantum mechanical system can be expanded, the understanding of their solubility is quite
important in any algebraic study of a quantum mechanical system. The analysis has been
carried out with generalized raising and lowering operators for the hypergeometric equation.
On the Geometric Implications of Maxwell's Equations

Felix T. Smith

A new examination of the structure of Maxwell’s equations shows that their self-consistency implies a constraint on the geometry of the medium in which electromagnetic processes take place that is not compatible with the four-dimensional space-time proposed by Minkowski. Instead the underlying geometry is best described as a 3-dimensional position space that is not quite Euclidean, having a homogeneous 3-space curvature that is negative and time dependent. Its radius of curvature is then imaginary, and increases in absolute magnitude linearly with time at a rate measured by $ic$. This provides direct, independent, quantitative evidence confirming the geometry of the Hubble expansion through entirely local effects observed at the present time in the measurable phenomena of electricity, magnetism and light. Important consequences follow directly for special relativity and its applications in atomic processes through the Dirac equation.