Half metallic antiferromagnetic ordering of cold fermions induced by resonant tunneling

Kazuto Noda, Kensuke Inaba, Makoto Yamashita

1. NTT Basic Research Laboratories, NTT Corporation, Atsugi 243-0198, Japan

An optical superlattice enables us to simulate the Hubbard model with staggered lattice potential by widely varying the onsite interaction U and the level difference Δ. When U=Δ, the resonant tunneling drastically changes the dynamical properties of atoms providing us with an opportunity to study novel quantum magnetism. The recent experiment utilizes this tunneling mechanism to reveal the magnetic phases of the Ising model [1].

We investigate the phase diagram of the staggered Hubbard model of two component fermions using the dynamical mean-field theory. We find that the resonant tunneling induces the novel half-metallic antiferromagnetic phase, where one spin component is metallic and the other is insulating. At finite temperatures, we find the emergence of this phase at half-filling without spin imbalance. On the other hand, at T=0, this phase only appears in the region away from half-filling.

References

[1] J. Simon, W. S. Bakr, R. Ma, M. E. Tai, P. M. Preiss, and M. Greiner,, Nature 472, 307 (2011).

New Quantum Simulation with Multi-component Fermi Gases

Guido Pagano[1, 2], Marco Mancini[1, 3], Giacomo Cappellini[1], Pietro Lombardi[1, 3], Florian Schaefer[1], Carlo Sias[1, 4], Jacopo Catani[1, 4], Massimo Inguscio[1, 3, 4], Leonardo Fallani[1, 3, 4]

1. LENS European Laboratory for Nonlinear Spectroscopy, Sesto Fiorentino 50019, Italy
2. Scuola Normale Superiore, 56126 Pisa, Italy
3. Department of Physics and Astronomy, University of Florence, Sesto Fiorentino 50019, Italy
4. INO-CNR Istituto Nazionale di Ottica del CNR, Sezione di Sesto Fiorentino, Sesto Fiorentino 50019, Italy

I will report on the latest results in the Ytterbium lab at LENS where we achieved quantum degeneracy of fermionic ^{173}Yb. The specific features of this atomic element provide a powerful test bench for large-spin models ranging from quantum simulation of spinful one-dimensional (1D) systems to the realization of spin-orbit coupling in multicomponent ultracold fermions. The realization of 1D, strongly-correlated liquids of ultracold fermions interacting repulsively [1] with a tunable number N of spin components is reported. We observe that static and dynamic properties of the system deviate from those of ideal fermions and, for $N>2$, from those of a spin-1/2 Luttinger liquid. In the large-N limit, the system exhibits properties of a bosonic spinless liquid. I will also show some preliminary results and perspectives on the physics of a spin-orbit coupled multicomponent Fermi gas accessible by opportunely engineering Raman couplings between the nuclear spin components of ^{173}Yb.

References

[1] G. Pagano, M. Mancini, G. Cappellini, P. Lombardi, F. Schaefer, H. Hu, X.J. Liu, J. Catani, C. Sias, M. Inguscio, L. Fallani, A one-dimensional liquid of fermions with tunable spin, Nature Physics 10, 198-201 (2014)

Ultracold Dysprosium gases: towards a topological superfluid

Davide Dreon, Chayma Bouazza, Wilfried Maineult, Leonid Sidorenkov, Tian Tian, Sylvain Nascimbène, Jean Dalibard

1. *Laboratoire Kastler Brossel*
2. *Collège de France*
3. *École normale supérieure*
4. *UPMC*
5. *CNRS*

We present a new experimental setup on ultracold Dysprosium gases. The current status of the project is the realization of a magnet-optical trap using a narrow-line optical transition. Dysprosium atoms present an electronic structure suitable for obtaining synthetic spin-orbit coupling with very low heating rate compared to alkali atoms. The modification of the Fermi surface due to this artificial coupling can lead to an effective spin-polarized Fermi gas with p-wave interactions, whose superfluid phase will present topologically non-trivial features. In particular, the edge excitations associated with the superfluid phase - that can be described as Majorana's fermonic quasiparticles - are expected to be strongly localized at the boundaries of the system and to have an energy lying in the middle of the superfluid gap.

Fermi Gases Tu-004

Breakdown of Landau’s Fermi liquid theory in a Strongly Interacting Fermi Gas

Tara Drake, Yoav Sagi, Rabin Paudel, Roman Chapurin, Deborah Jin

1. *JILA, University of CO, Boulder and NIST*

We present a novel measurement of the single particle spectral function for a homogeneous Fermi gas above the critical temperature throughout the BCS-BEC crossover. We observe that the dispersion can be fitted extremely well by a function composed of two parts: the spectral function of bound pairs and that of a Landau Fermi liquid (FL). We find that already at unitarity, the FL theory is largely unsuited to describe the data, which exhibits a predominantly pair-like dispersion. For diminishing attractive interactions, the spectral function converges to that expected by a FL, from which we get the effective mass of the fermionic quasiparticle. Our data reconciles different past experimental observations by showing how the many-body behavior of fermions in the BCS-BEC crossover changes from a FL to a molecular bose gas over a rather small region.

Diffusion of spin in a unitary Fermi gas

Scott Smale[1], Chris Luciuk[1], Scott Beattie[1], William Cairncross[1], Alma Bardon[1], Stefan Trotzky[12]
, Joseph Thywissen[1, 2]

1. *University of Toronto*
2. *Canadian Institute for Advanced Research*

Understanding the non-equilibrium dynamics of strongly interacting particles is one of the current challenges in physics. We have investigated spin transport for a degenerate Fermi gas of 40K atoms in the unitary regime. As our initially spin polarized gas relaxes we find that to properly characterize the magnetization dynamics one must consider the Leggett-Rice spin rotation effect in addition to spin diffusion. Using a Feshbach resonance to access the unitary regime we probe our entire cloud using NMR-like spin echo sequences. We have quantified both the spin diffusion and the Leggett-Rice effect and their dependence on temperature and interaction strength.

Exploring the phase diagram of a strongly interacting 2D Fermi gas

Gerhard Zürn[1], Luca Bayha[1], Druvh Kedar[1], Thomas Lompe[2], Puneeth Murthy[1], Mathias Neidig[1]
, Martin Ries[1], Andre Wenz[1], Selim Jochim[1]

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

We present our experiments on ultracold fermions trapped in a two-dimensional potential and report on the observation of a quasi-condensate of fermion pairs. For this measurement we prepare a quantum degenerate gas of ^{6}Li atoms in the two lowest hyperfine sublevels confined in a single layer of a standing wave optical dipole trap. A magnetic Feshbach resonance allows us to tune the interaction strength in the system from the weakly to the strongly interacting regime. By using a matter wave focussing technique we obtain the radial momentum distribution of our sample and observe a bimodal distribution of a thermal cloud and a low-momentum condensate. Self-interference of the condensate indicates quasi long range phase coherence as theoretically predicted for a BKT-like phase. By measuring the condensed fraction as a function of temperature and interaction strength we map out the phase diagram of a strongly interacting two-dimensional Fermi gas.

Fermi Gases Tu-007

Experimental studies of an interacting 2D Fermi Gas

Tyson Peppler[1], Kristian Fenech[1], Marcus Lingham[1], Paul Dyke[1], Sascha Hoinka[1], Chris Vale[1]

1. Swinburne University of Technology

Ultracold Fermi gases allow unique insight into the behaviour of particles at the quantum level. Manipulation of parameters associated with interaction and confinement can also lead to the creation of exotic phases of matter. Specifically, 2D Fermi gases will open the way to studies of the crossover from a Bardeen-Cooper-Schrieffer to Berezinskii-Kosterlitz-Thouless superfluidity as the strength of attractive interactions are tuned via a Feshbach resonance. By application of a cylindrically focussed blue-detuned TEM01 mode laser we confine Fermi gases of lithium-6 atoms to 2D by making the vibrational states of the harmonic potential in the transverse direction energetically inaccessible compared to the radial. Here we present data showing the transition from 2D to quasi-2D in a Fermi gas with tunable interactions as well as our progress towards a precise determination of the thermodynamic equation of state.

Fermi Gases Tu-008

Production of a degenerate fermi gas of chromium

Laurent Vernac[1], Bruno Naylor[1], Antoine Reigue[1], Etienne Maréchal[1], Olivier Gorceix[1], Bruno Laburthe-Tolra[1]

1. Laboratoire de Physique des Laser, Université Paris 13, 99 Avenue Jean Baptiste Clément, 93430 Villetaneuse, France

I will present recent results we have obtained for the cooling of the fermionic chromium isotope ^{53}Cr. As for the bosonic isotope, our strategy has been to load directly in a far detuned dipole trap atoms in metastable states produced in a MOT [1]. As the fermionic MOT is disturbing the bosonic MOT [2], we first load the dipole trap with fermions, and then with bosons, before starting sympathetic cooling. We have optimized the dipole trap geometry to obtain 10^{6} bosons with 3.10^{4} fermions before evaporation in a crossed dipole trap.

Analysis of populations show an almost suppression of fermionic atoms losses way before the end of the evaporation ramp. Preliminary measurements indicate a large boson-fermion scattering length compatible with a bosonic assisted hydrodynamic regime for the fermions.

We obtain $10^{3}{}^{53}$Cr atoms at a temperature of 250 nK, while the Fermi Energy is estimated at 330 nK.

References

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

Bose Gases Tu-009

ZNG – Theory for Dipolar Quantum Gases

Vladimir Veljić[1], Antun Balaž[1], Axel Pelster[2]

1. Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Serbia
2. Department of Physics and Research Center Optimas, Technical University of Kaiserslautern, Germany

We study harmonically trapped three-dimensional ultracold Bose and Fermi gases in the presence of the short-range isotropic contact and the long-range anisotropic dipole-dipole interaction (DDI). The Hartree-Fock mean-field dynamics of such quantum systems can be described within the framework of the Zaremba-Nikuni-Griffin (ZNG) theory. Usually, the underlying Boltzmann-Vlasov (BV) equation is solved by the relaxation-time approximation for the collision integral, where the relaxation time is treated as a phenomenological parameter. We develop a formalism to determine the relaxation time microscopically for ultracold quantum gases at finite temperature, which allows us to include collision effects self-consistently in the BV formalism.

Bose Gases Tu-010

Dynamics of spinor condensates in a microwave dressing field

Lichao Zhao[1], Jie Jiang[1], Tao Tang[1], Micah Webb[1], Yingmei Liu[1]

1. Department of Physics, Oklahoma State University

We experimentally study dynamics in a sodium antiferromagnetic spinor condensate as a result of spin-dependent interactions c and microwave dressing field interactions characterized by the net quadratic Zeeman effect q_{net}. In contrast to magnetic fields, microwave dressing fields enable us to access both negative and positive values of q_{net}. We find an experimental signature to determine the sign of q_{net}, and observe harmonic spin population oscillations at every q_{net} except near each separatrix in phase space where spin oscillation period diverges. Our data in the negative q_{net} region exactly resembles what is predicted to occur in a ferromagnetic spinor condensate in the positive q_{net} region. This observation agrees with an important prediction derived from the mean-field theory: spin dynamics in spin-1 condensates substantially depends on the sign of q_{net}/c. This work may be the first to use only one atomic species to reveal mean-field spin dynamics, especially the remarkably different relationship between each separatrix and the magnetization, of spin-1 antiferromagnetic and ferromagnetic spinor condensates.

Non-Equilibrium Dynamics of Component Separation in a Binary Bose Gas

Nick Proukakis[1], Rob Pattinson[1], Nick Parker[1]

1. Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics & Statistics, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

Binary mixtures of atomic Bose gases provide a platform for studying rich phenomena at the interface of atomic physics, nonlinear waves and nonequilibrium dynamics, driven by the nonlinear interactions between the two species. Commonly, a single-species Bose gas is first formed and then a proportion of the atoms are coherently transferred to a second hyperfine state. This transfer, instantaneous with respect to the external gas dynamics, places the system in a nonequilibrium state. Using a classical field description, we model the formation and subsequent thermalization of this nonequilibrium state, mapping the dependence on the nonlinear interactions and the proportion of transferred atoms. In general we find that component separation leads to a reduction of condensate fraction and an associated heating of the system which, in certain regimes, can be considerable. Furthermore, we discuss the formation of topological defects - domains and vortex excitations - during these dynamics.

Nonlinear interferometric scaling from spin-mixing density oscillations

Khan Mahmud[1], Phil Johnson[2], Eite Tiesinga[1]

1. Joint Quantum Institute, University of Maryland and NIST, Maryland, USA
2. American University, DC, USA

We show that spin-dependent atom-atom interaction strengths for spin-1 atoms in an optical lattice can be measured with super-Heisenberg scaling as a function of the number of atoms per lattice site. In our proposal, a superfluid ground state in a shallow lattice is suddenly quenched by increasing lattice depth, creating a nonequilibrium state where atom-atom spin-exchange collisions drive oscillations of the different spin component populations. We show that in-situ measurements of the spin-population dynamics can yield the interaction strengths with super-Heisenberg scaling. We further explore how the scaling behavior depends on the initial ground state. Since spin-mixing density oscillations have already been observed with spin-1 atoms in a harmonic trap, demonstrating this scaling behavior should be within experimental reach.

Kinetic Model of a Finite Temperature Multi-Component Condensate

M. J. Edmonds[1], Kean Loon Lee[1], N. P. Proukakis[1]

1. Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics and Statistics, Newcastle University, Newcastle upon Tyne NE1 7RU, England, UK

We construct a finite temperature theory describing the out of equilibrium dynamics of two interacting Bose-Einstein condensates. This is accomplished by treating the non-condensed degrees of freedom with kinetic (Boltzmann) equations coupled to dissipative Schrödinger equations that describe the dynamics of the two condensates [1], [2]. It is shown that in comparison to a single component condensate, the additional density-density interaction between the condensates and thermal clouds facilitate a number of new transport processes, including the intra and inter-component collisional transfer of non-condensate and condensate atoms [3]. The importance of these new terms is quantified with realistic experimental parameters, by numerically calculating the collision rates for both intra and inter-component collisions.

References

[1] E. Zaremba, T. Nikuni, and A. Griffin, J. Low. Temp. Phys. 116, 277 (1999). [2] A. Griffin, Phys. Rev. B 53, 9341 (1996). [3] M. J Edmonds, Kean Loon Lee, N. P. Proukakis, in preparation (2014).

Mapping the phase diagram of spinor condensates via adiabatic quantum phase transitions

Jie Jiang[1], Lichao Zhao[1], Micah Webb[1], Yingmei Liu[1]

1. Department of Physics, Oklahoma State University, Stillwater, OK 74078

We experimentally study two quantum phase transitions in a sodium spinor condensate immersed in a microwave dressing field. We also demonstrate that many previously unexplored regions in the phase diagram of spinor condensates can be investigated by adiabatically tuning the microwave field across one of the two quantum phase transitions. This method overcomes two major experimental challenges associated with some widely used methods, and is applicable to other atomic species. Agreements between our data and the mean-field theory for spinor Bose gases are also discussed.

Fast thermalization and Helmholtz oscillations of an ultracold Bose gas

David J. Papoular[1], Lev P. Pitaevskii[1, 2], Sandro Stringari[1]

1. INO-CNR BEC Center and Dipartimento di Fisica, Universita di Trento, Italy
2. Kapitza Institute for Physical Problems, Moscow, Russia

We analyze theoretically the transport properties of a weakly-interacting ultracold Bose gas enclosed in two reservoirs connected by a constriction. We assume that the transport of the superfluid part is hydrodynamic, and we describe the ballistic transport of the normal part using the Landauer-Buttiker formalism. Modeling the coupled evolution of the phase, atom number, and temperature mismatches between the reservoirs, we predict that Helmholtz (plasma) oscillations, induced by an initial imbalance in atom numbers, can be observed at non-zero temperatures below Tc. We show that, because of its strong compressibility, the ultracold Bose gas is characterized by a fast thermalization compared to the damping time for plasma oscillations, accompanied by a fast transfer of the normal component through the constriction. This fast thermalization also affects the gas above Tc, where we present an explicit comparison to the ideal fermionic case.

BEC dynamics with solitons and vortices

André de Freitas Smaira[1], Mônica Andrioli Caracanhas[1], Vanderlei Salvador Bagnato

1. Physics Institute of São carlos, University of São Paulo

Bose-Einstein Condensates (BEC) are excellent macroscopic systems to observe the quantum behavior of matter. Since its experimental production [1], there are important aspects related to this system that have been intensively explored, like the collective modes of the BEC in harmonic trap [2], its tunneling through a potential barrier [3] and the excited states of this system (including vortices and solitons) [4,5]. In this work, we investigate the singular aspects that coming from the tunneling of a composite system: a trapped BEC containing an excitation. We studied the energy exchange between the two subsystems and the movement frequency changes to explain the new aspects presented by our system.

References

[1] W. Ketterle, Rev. Mod. Phys. 74, 1131 (2002)
[2] L. Pitaevskii and S. Stringari, Bose-Einstein Condensation, book
[3] Z. Duan, B. Fan, C.-H. Yuan, J. Cheng, S. Zhu and W. Zhang, Phys. Rev. A 81, 055602 (2010)
[4] C. J. Pethick and H. Smith, Bose-Einstein Condensation in Dilute Gases, book
[5] N. Parker, Numerical studies of vortices and dark solitons in atomic Bose-Einstein condensates, Doctoral thesis, Durham University

Production of Two Species Superfluid to Study Quantum Turbulence and Vortices.

Kilvia Mayre Farias[1], Edwin Eduardo Pedrozo-Peñafiel[1], Franklin Vivanco[1], Patricia Castilho[1], Anne Louise Kruger[1], Giacomo Roati[2], Daniel Varela Magalhães, Vanderlei Bagnato[1]

1. *Instituto de Física de São Carlos - Universidade de São Paulo*
2. *LENS and Dipartimento di Fisica e Astronomia, Università di Firenze, and INO-CNR, 50019 Sesto Fiorentino, Italy*

In this work we are dealing with a mixture of Na/K Bose-Einstein Condensates. With the mixture of these two superfluids, we are going to investigate effects of transferring quantum excitations, vortices formation and quantum turbulence, as well. Effects of modulation of the scattering length and excitation will be object of investigation in the BEC of K verifying the consequences on the second specie (Na). Our experimental system is a composition of two independently atomic sources attached to a main chamber. We produce magneto-optical traps of Na and K atoms from 2D MOTs, which utilize a novel Zeeman slower configuration [1]. The whole system size is of the order of the previous standard Zeeman slower we had only for Na atoms. A next step is transferring the atoms to a crossed dipole trap and performing the experiments.

References

[1] S. Donadello, M.Sc. thesis, University of Trento, 2012.

Coherent matter wave propagation with BECs in toroidal guiding potentials for atom interferometry and ATOMTROMICS based quantum simulators

Gerhard Birkl[1], Johannes Kueber[2], Felix Schmaltz[3], Thomas Lauber[4]

1. *Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstrasse 7, 64289 Darmstadt, Germany*

We are establishing a novel platform for the application of BEC-based coherent matter waves in toroidal guiding geometries for ATOMTRONICS devices (such as atomic SQUIDS), atom interferometry, and quantum simulation. Our architecture is based on a novel type of toroidal dipole-force potential generated by conical refraction providing a pair of concentric annular intensity distributions. Depending on detuning, these serve as a concentric pair of red-detuned potential minima or as a single blue-detuned potential minimum. By changing the parameters of the refractive crystal and the impinging laser beam, ring diameter and well dimensions can be varied with high flexibility. We load BECs into a ring with 340 micron diameter and accelerate or split the wave function by Bragg diffraction. We rotate the wave function with 2 or 4 photon momenta or create two partial waves with +2 and -2 photon momenta. Before and after rotation we perform interferometric coherence measurements.

Towards producing atomic circulations in a toroidal trap in a Rb87 Bose-Einstein condensate

Cheng-An Chen, Jung-Bin Wang, Pan-Pan Huang, Chin-Yeh Yu, Yu-Ju Lin

1. *Institute of Atomic and Molecular Sciences, Academia Sinica*

We have designed a setup to experimentally study atomic circulations of ultracold atoms in a ring-shaped trapping potential. To make Bose-Einstein condensates (BEC) of Rb87 atoms, we first capture zeeman-slowed atoms in a MOT, perform polarization gradient cooling, and then load the atoms into a quadrupole magnetic trap. After 3.5s of rf-evaporation, these pre-cooled atoms are transferred into a hybrid potential, a crossed optical dipole trap with a weak magnetic confinement. We perform evaporative cooling for 9s in the dipole trap, and a condensate with 3e5 atoms is produced. Our next step is to load the atoms into a toroidal dipole trap and use two Raman beams with orbital angular momentum to create synthetic magnetic flux, thus generating atomic circulations.

A continuous atom laser extracted from sodium condensates using two-photon Raman transition

Motoyuki Murakami[1], Shinya Okuoka[1], Atsuo Morinaga[1]

1. *Tokyo University of Science*

Using the two-photon stimulated Raman transition, a partial of sodium condensates in the un-trapped state was extracted continuously during 8 ms from the main Bose-Einstein condensates trapped in the cloverleaf trap. The two-photon Raman beams with a Rabi frequency of $2\pi\times800$ Hz and the frequency difference between two Raman beams of $2\pi\times890$ kHz were applied to the Bose-Einstein condensates with a number of 10^7 atoms. The intersection angle between two Raman laser beams was 80 degrees at the condensates. The condensates in the un-trapped state transited by the two-photon Raman beam were extracted with a recoil velocity from the main condensates in the trapped state. The beam divergence angle of the atom laser was 3.0 ± 1.5 mm/s. The coherence properties of the atom laser were discussed.

Observation of a reduced damping rate of collective oscillations of a quasi-1D Bose-Einstein condensate

Ben Yuen[1, 2], Iain Barr[1], Joseph Cotter[1, 3], Eoin Butler[1], Ed Hinds[1]

1. Centre for Cold Matter, Imperial College London.
2. National Physical Laboratory, UK.
3. Vienna Center for Quantum Science and Technology.

We investigate the damping of the collective centre-of-mass motion of a quasi-one-dimensional Bose-Einstein condensate at finite temperature, magnetically trapped on an atom chip. We find that the observed damping rate is more than three times slower than that predicted by the Landau damping theory for a three-dimensional uniform gas [1]. We present a simple model in which a discrete level spectrum is imposed on the system by defining a finite transverse width. We show that this simple model matches the experimental measurements well when this width is of the order of the width of the condensate. Furthermore, our theory predicts that changing the transverse width of the system can vary the damping rate over a broad range.

References

[1] L. P. Pitaevskii and S. Stringari, Physics Letters A 235, 398 (1997)

Spin dynamics in a two dimensional quantum gas

Poul Pedersen[1], Miroslav Gajdacz[1], Frank Deuretzbacher[2], Luis Santos[2], Carsten Klempt[3], Jacob Sherson[1], Andrew Hilliard[1], Jan Arlt[1]

1. Institut for Fysik og Astronomi, Aarhus Universitet, Ny Munkegade 120, 8000 Aarhus C, Denmark
2. Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany
3. Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

We have investigated spin dynamics in a 2D quantum gas. Through spin-changing collisions, two clouds with opposite spin orientations are spontaneously created in a Bose-Einstein condensate. After ballistic expansion, both clouds acquire ring-shaped density distributions with superimposed angular density modulations. The density distributions depend on the applied magnetic field and are well explained by a simple Bogoliubov model. We show that the two clouds are anti-correlated in momentum space. The observed momentum correlations pave the way towards the creation of an atom source with non-local Einstein-Podolsky-Rosen entanglement.

Vortex Pair Annihilation in Two-Dimensional Superfluid Turbulence

Woo Jin Kwon, Geol Moon, Jae-yoon Choi, Sang Won Seo, Yong-il Shin

1. Center for Subwavelength Optics and Department of Physics and Astronomy, Seoul National University, Seoul

We investigate thermal relaxation of two-dimensional superfluid turbulence in a highly oblate Bose-Einstein condensate. We identify annihilation of vortex-antivortex pairs by directly observing coalesced vortex cores with a crescent shape and their disappearing as being filled with atoms. The vortex number of the condensate exhibits nonexponential decay behavior due to the vortex pair annihilation process. We measure the two-body decay rate of the vortex number for various sample conditions and find that the local decay rate is proportional to T^2/μ, where T is the temperature and μ is the chemical potential.

References

[1] W. J. Kwon, G. Moon, J. Choi, S. W. Seo, and Y. Shin , "Vortex Pair Annihilation in Two-Dimensional Superfluid Turbulence", arXiv:1403.4658 (2014)

Bethe ansatz approach to prethermalization in a coherently split 1D Bose gas

Eriko Kaminishi, Tatsuhiko Ikeda, Takashi Mori, Masahito Ueda

1. Department of Physics, Graduate Schools of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

We discuss the prethermalization dynamics of a coherently split one-dimensional Bose gas by using the Bethe ansatz method. Prethermalization is a relaxation process to a quasi-stationary state before reaching the true equilibrium state. The concept of prethermalization is important for understanding the fundamental aspects of quantum statistical mechanics such as “equilibration” and “relaxation” in isolated quantum many-body systems. Prethermalization and its connection to integrability in one-dimensional quantum systems have been intensively studied experimentally and theoretically. For instance, M. Gring et al. [1] recently observed the evolution of a rapidly and coherently split 1D Bose gas for large numbers of particles and compare the evolution of the system to the prediction of the Tomonaga-Luttinger liquid (TLL) theory.

Here we argue that the splitting of the 1D Bose gas is formulated by a kind of quantum quench, and precisely analyze the prethermalization process over a long-time scale beyond the TLL prediction.

References

[1] M. Gring, M. Kuhnert, T. Langen, T. Kitagawa, B. Rauer, M. Schreitl, I. Mazets, D. Adu Smith, E. Demler, and J. Schmiedmayer, Science 337,1318 (2012).

Enhanced scattering in a Bose-Einstein condensate and a measurement of the heat capacity.

Pieter Bons[1], Peter van der Straten[1]

1. Nanophotonics, Debye Institute, Center for Extreme Matter and Emergent Phenomena, Utrecht University, The Netherlands

We study the refractive index of an ultra-cold bosonic gas in the dilute regime. Our atomic clouds are analyzed for temperature and particle number using nearly non-destructive phase-contrast imaging with light detuned from resonance by several tens of linewidths. After each pulse of probe light a small fraction of the atoms is lost, while the cloud is simultaneously slightly heated, allowing us to study the scattering rate as a function of temperature using only a single sample. We observe that the scattering rate increases below the critical temperature for Bose-Einstein condensation by more than a factor of 3 compared to the classical value. Our results are in fair agreement with the predictions by Morice et al. which take two-body correlation and resonant Van-der-Waals forces into account [1]. Currently we are expanding our method to perform calorimetry and directly measure the heat capacity of the BEC.

References

[1] O. Morice,Y. Castin and J. Dalibard, Phys. Rev. A 51, 3896 (1995)

Bose Gases Tu-026

Atom chip based ultracold potassium for testing microwave and RF potentials

Austin Ziltz[1], Charles Fancher[1], A. J. Pyle[1], Seth Aubin[1]

1. College of William & Mary

We present progress on an experiment to manipulate and trap ultracold atoms with microwave and RF (μ/RF) AC Zeeman potentials produced with an atom chip. These μ/RF potentials are well suited for atom interferometry and spin-dependent trapping for 1D many-body physics studies due to their ability to operate in conjunction with magnetic Feshbach resonances to tune interactions. Calculations show that μ/RF potentials will significantly suppress the inherent atom chip roughness associated with DC magnetic potentials. We have assembled a dual species, dual chamber apparatus that produces ultracold ^{39}K samples and ^{87}Rb Bose-Einstein condensates on an rf-capable atom chip, with access to other isotopes. On-chip ^{39}K will be sympathetically cooled through the microwave evaporation of rubidium, and transferred to a co-located dipole trap for a series of spatial manipulation experiments to study the capabilities and performance of μ/RF potentials.

Bose Gases Tu-027

Experimental Investigation Of Quantum Turbulence in a Trapped Superfluid

P. Tavares[1], G. Telles[1], E. Henn[1], A. Fritsch[1], A. Bahrani[1], Y. R. Tonin[1], V. S. Bagnato[1]

1. Instituto de Fisica de São Carlos - Universidade de São Paulo - Brasil

Continuing our recent work on the demonstration of emergence of a turbulent regime in a sample of trapped super fluid Rb atoms we present new features associated with it. The main aspects of vortices formation, proliferation are described in terms of amplitude and time of excitation. Using free expansion we obtain the momentum distribution n(k). The analysis is performed to identify the inertial range of momentum and associated with the appearance of the power law dependence . Details of the experiment are presented. The verification of a direct cascade of energy during the time evolution for a turbulent cloud is described. Evolution of the turbulent state to granulation and codnensate destruction are discussed. Finally, arguments are presented concerning the importance of the phenomenon of quantum turbulence in trapped atoms and the new window of opportunities in this new modality of experiments. Support from FAPESP, CNPq and CAPES . We thanks the productive collaboration with *A. Fetter, V. Yukalov ,R. Hulet , A. N. Novikov and M. Tsubota*

Bose Gases Tu-028

Thermodynamics With Global Variables For a Trapped Bose Gas

V. S. Bagnato[1], S. R. Muniz[1], G. D. Telles[1], R. F. Shiozaki[1], P. Castilho[1], F. J. Poveda-Cuevas [1], G. Roati[2]

1. Instituto de Física de São Carlos - Universidade de São Pulo, Brasil
2. LENS and Universita` di Firenze, Via Nello Carrara 1, 50019 Sesto Fiorentino, Italy

Using the concept of Global Variable we have characterized the Bose condensation for a trapped Bose gas. First, a pair of global conjugate variables is defined then we determine the system's total internal energy and its temperature derivative, the heat capacity. In a ^{87}Rb BEC, a rapidly changing C_V was observed, in the vicinity of the critical temperature, T_c, in close similarity to the lambda point in liquid ^{4}He. In a second set of measurements we have determined the isothermal compressibility, showing that k_T obeys the Curie law. Recovering ideas initially proposed by Niels Bohr, we measured an uncertainty type relation between the global *pressure* and *volume* of a Bose-Einstein Condensate of ^{87}Rb atoms trapped in a hybrid trap determining the relation of the minimal possible values for pressure and volume parameters showing that at T=0 they cannot be simultaneously zero . In a future perspective we are planning the use of global variable thermodynamics to characterize variations present in a turbulent cloud of trapped BEC. Figures showing(in the sequence):Phase diagram, Heat capacity, isothermal compressibility and relations of pressure volume at minimum number at T=0. Work supported by FAPESP, CNPq and CAPES.

Bose-Einstein Condensation of ^{86}Sr

Ben Reschovsky[1], Daniel Barker[1], Neal Pisenti[1], Gretchen Campbell[1]

1. JQI, NIST and University of Maryland

We report on the successful Bose-Einstein condensation of ^{86}Sr and the measurement of the ^{86}Sr three-body decay rate in a thermal gas. The cooling cycle includes two MOT stages and evaporative cooling in an optical dipole trap. Due to the large scattering length ($a = 823a_0$) of ^{86}Sr, evaporation must be performed at low density and proceed quickly in order to avoid loss due to three-body recombination. We are able to reliably generate pure condensates of about 20,000 atoms. Future work will include the investigation of optical Feshbach resonances as well as optical lattice experiments.

QUANTUM SIMULATION

Non-equilibrium wave-packet dynamics in 1D optical lattices

Alexandre B. Tacla[1, 2], Stephan Langer[2], Andrew Daley[1, 2]

1. Department of Physics, University of Strathclyde
2. Department of Physics and Astronomy, University of Pittsburgh

We study the non-equilibrium dynamics of localized density excitations in systems of ultracold atoms in Bose-Hubbard lattices. In particular, we investigate transport and interferometry properties via wave-packet propagation in one-dimensional and Y-junction geometries. By means of time-dependent Density Matrix Renormalization Group methods, we study the quantum many-body dynamics on the lattice and correlations between excitations in the strongly interacting, superfluid regime. Direct comparison to the solution of the time-dependent, discrete nonlinear Schrodinger equation reveals characteristic features of the dynamics of these excitations that cannot be captured by such a simplified mean-field description, which typically describes wave excitations in the weakly interacting, superfluid regime.

A Dissipative Quantum Many-Body System with Long-Range Interactions

Rafael Mottl[1], Renate Landig[1], Lorenz Hruby[1], Ferdinand Brennecke[1, 2], Tobias Donner[1], Tilman Esslinger[1]

1. Institute for Quantum Electronics, ETH Zurich, Switzerland
2. University Bonn

A Bose-Einstein condensate whose motional degrees of freedom are coupled to a high-finesse optical cavity via a transverse pump beam constitutes a dissipative many-body system with long-range interactions. The cavity-mediated long-range interactions drive the atomic cloud from a superfluid to a supersolid phase. As the transverse pump field constantly probes the atomic density via cavity-enhanced Bragg scattering, it maps the density fluctuations to the intracavity field which we monitor in real-time. Using heterodyne detection, we spectroscopically resolve the cavity output field which contains the dynamic structure factor of the atomic gas. We extract the critical exponents of diverging density fluctuations on both sides of the phase transition. They deviate from the closed-system values and show the dissipative character of the system due to the leaking cavity field. In addition, we investigate the competition between cavity-mediated long-range interactions and short-range contact interactions by loading into deep two-dimensional optical lattices.

Quantum Simulation Tu-032

Dissipative Transport in a Many Body Quantum System

Bodhaditya Santra, Ralf Labouvie, Simon Heun, Herwig Ott

1. Research Center OPTIMAS and Fachbereich Physik, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

Understanding the effect of intrinsic dissipation on the transport mechanism of a many body quantum system is one of the essential task as it plays an important role in many areas ranging from mesoscopic conduction to molecular electronics. We experimentally realize such a quantum transport system and investigate the influence of dissipation on the transport of particles. We prepare our system by loading Bose condensed ^{87}Rb in a 1D optical lattice with high atom occupancy per lattice site. Subsequently we remove all the atoms from a central lattice site. While the atoms from neighboring sites tunnel into the empty site, we observe a clear signature of on site dissipation on the tunneling transport mechanism.

Ballistic Atom Pumps

Tommy Byrd[1], Megan Ivory[1], A.J. Pyle[1], Kunal Das[2], Kevin Mitchell[3], Seth Aubin[1], John Delos[1]

1. Department of Physics, College of William and Mary, Williamsburg, VA 23187, USA
2. Department of Physical Sciences, Kutztown University of Pennsylvania, Kutztown, PA 19530, USA
3. School of Natural Sciences, University of California, Merced, CA 95344, USA

Researchers have long been interested in electron transport through mesojunctions containing time-dependent potential barriers, a process often called ``quantum pumping.'' A useful model of such a system is a ballistic atom pump: two reservoirs of neutral ultracold atoms connected by a channel containing oscillating repulsive potential-energy barriers. This system can create net particle transport in either direction, and, even if there is no net particle transport, energy can be pumped out of or into each reservoir. We also show a ``particle rectifier'' which under specified conditions permits net particle pumping in only one direction. Classically, this system is a nice model of chaotic transport, and the quantum description cannot be fully understood without analyzing the underlying classical dynamics. We use classical trajectories, along with phase information, to construct a semiclassical approximation to the quantum description. This approach explains the locations and relative heights of Floquet peaks seen in quantum theory.

The effects of phase noise on the delta-kicked rotor

Maarten Hoogerland[1], Donald White[1], Sam Ruddell[1]

1. Department of Physics, University of Auckland, New Zealand

We report on the effects of phase noise in the atom-optics implementation of the delta-kicked rotor. A paradigm for experiments on quantum chaos, this system has demonstrated dynamic localisation and ballistic energy growth as a function of the number of kicks for different kick periods [1], and the influence of amplitude and frequency noise on the kicks has been studied [2].

In the experiment we report on here, we start with an all-optical BEC of ^{87}Rb atoms, and subject it to a kick sequence at the anti-resonance, where subsequent kicks destructively interfere. We modulate the phase of the kicks, with an adjustable frequency and amplitude. We observe resonances, conversion from localisation to ballistic growth and sub-diffusion in this system.

References

[1] M. G. Raizen. Quantum chaos with ultra-cold atoms. Adv. At. Mol. Opt. Phys., 41:43, (1999).
[2] Mark Sadgrove, Andrew Hilliard, Terry Mullins, Scott Parkins, and Rainer Leonhardt, Phys. Rev. E 70, 036217 (2004).

Dynamics of atoms in bilayer optical lattices, and adiabatic state preparation

Stephan Langer[1], Andrew Daley[2]

1. University of Pittsburgh
2. University of Strathclyde

We study ultracold quantum gases trapped in optical lattices consisting of two layers (which can each either be one-dimensional or two-dimensional). We propose schemes for adiabatic state preparation of low-entropy states of bosons and fermions given tunable inter-layer couplings. In this context it is possible, to use one layer as an entropy reservoir, which removes entropy from the other layer, before decoupled from it. For the case of two coupled one-dimensional layers, we calculate the time-dependent dynamics exactly using the time-dependent density matrix renormalization group technique and identify parameter regimes such entropy transfer occurs, and the emergence of characteristic many-body correlations in the low-entropy layer can be observed. This process is especially effective when the desired state in the low-entropy layer is gapped, and these states can be used as a starting point also for other adiabatic preparation protocols, including the realisation of metastable excited states.

Quantum Simulation Tu-036

Observation of a disordered bosonic insulator from weak to strong interactions

Chiara D'Errico[1, 2], Eleonora Lucioni[1, 2], Luca Tanzi[2], Lorenzo Gori[2], Guillaume Roux[3], Ian P. McCulloch[4], Thierry Giamarchi[5], Massimo Inguscio[2, 7], Giovanni Modugno[1, 2]

1. Istituto Nazionale di Ottica, CNR, 50019 Sesto Fiorentino, Italy
2. LENS and Dipartimento di Fisica e Astronomia, Università di Firenze, 50019 Sesto Fiorentino, Italy
3. LPTMS, Univ. Paris-Sud, CNRS, F-91405 Orsay, France
4. Centre for Engineered Quantum Systems, University of Queensland, Brisbane 4072, Australia
5. DPMC-MaNEP, University of Geneva, 1211 Geneva, Switzerland
6. INRIM, 10135, Torino, Italy

Understanding the behavior of disordered, interacting systems is one of the challenges of quantum physics. We employ ultracold atoms with controllable disorder and interaction to study the paradigmatic problem of disordered bosons in the full disorder-interaction plane. Combining measurements of coherence, transport and excitation spectra, we get evidence of an insulating regime extending from weak to strong interactions and surrounding a superfluid-like regime, in general agreement with the theory [1]. For strong interaction, we reveal the presence of a strongly-correlated Bose glass coexisting with a Mott insulator. For weak interaction, we also study the momentum-dependend transport, finding a sharp crossover from a weakly dissipative regime to a strongly unstable one at a disorder-dependent critical momentum. The vanishing of this critical momentum can be used to locate the fluid-insulator transition driven by disorder [2].

References

[1] C. D’Errico et al.,arXiv:1405.1210.
[2] L. Tanzi et al., Phys. Rev. Lett. 111, 115301 (2013).

Quantum Simulation Tu-037

Particle-hole entanglement of ultracold atoms in an optical lattice

Ho-Tsang Ng

1. Institute for Interdisciplinary Information Sciences, Tsinghua University

We study the ground state of two-component bosonic atoms in a one-dimensional optical lattice. By applying an external field to the atoms at one end of the lattice, the atoms are transported and becomes localized at that site. The holes are then created in the remaining sites. The particle-hole superpositions are produced in this process. We investigate the entanglement entropy between the atoms in the two different parts of a lattice. A large degree of particle-hole entanglement is generated in the ground state. The particle-hole quantum correlations can be probed by the two-site parity correlation functions. The transport properties of the low-lying excited states are also discussed.

References

[1] H. T. Ng, Phys. Rev. A 88, 023621 (2013).

Quantized Scattering from an Oscillating Barrier for Atomic Quantum Pumps

Andrew Pyle[1], Megan Ivory[1], Austin Ziltz[1], Charles Fancher[1], Anuraag Sensharma[1], Seth Aubin[1], Tommy Byrd[1], John Delos[1], Kunal Das[2], Kevin Mitchell[3]

1. *College of William & Mary*
2. *Kutztown University of Pennsylvania*
3. *University of California, Merced*

We present progress on an experiment to study 1D quantum mechanical scattering by an amplitude-modulated barrier. Numerical simulations confirm the oscillating barrier imparts or subtracts kinetic energy from the scattered atoms in discrete amounts of $\hbar\omega$, where ω is the modulation frequency. We present an atom chip-based experimental system to study the scattering dynamics by directing Bose-Einstein condensates (BEC) of ^{87}Rb at a tightly focused, 532nm laser beam that serves as an oscillating barrier, located in the center of the trap. We present methods for measuring the scattering spectrum and the use of dark-ground imaging for high sensitivity detection. This experiment represents a first step toward implementing a quantum pump for ultracold atoms based on two such barriers modulated out of phase with one another.

A Dynamic, Ultra-Slow Optical-Matter Wave Analog of Event Horizon

C. J. Zhu[1], L. Deng[2], E. W. Hagley[2], Mo-Lin Ge[3]

1. *East China Normal University, Shanghai, China 200062*
2. *National Institute of Standards & Technology, Gaithersburg, Maryland USA 20899*
3. *Theoretical Physics Division, Chern Institute of Mathematics, NanKai University, Tianjin 300071, China*

We investigate theoretically the effects of a dynamically increasing medium index on optical-wave propagation in a rubidium condensate. A long pulsed pump laser coupling a D2 line transition produces a rapidly-growing internally-generated field. This results in a significant optical self-focusing effect and creates a dynamically growing medium index anomaly that propagates ultra-slowly with the internally-generated field. When a fast probe pulse injected after a delay catches up with the dynamically increasing index anomaly, it is forced to slow down and is prohibited from crossing the anomaly, thereby realizing an ultra-slow optical-matter wave analogue of a *dynamic* white-hole event horizon

References

[1] W. G. Unruh, Phys. Rev. D 51, 2827 (1995).
[2] L. Susskind, “Black holes and the information paradox”, Scientific American, (April issue).
[3] A. Cho, Science 319, 1321 (2008).
[4] T. G. Philbin et al., Science 319, 1367 (2008).
[5] A. Demircan, Sh. Amiranashvili and G. Steinmeyer, Phys. Rev. Lett. 106, 163901 (2011).
[6] E. A. Donley et al., Nature 412, 295-299 (2001).
[7] O. Lahav et al., Phys. Rev. Lett. 105, 240401 (2010).

Breaking of time-reversal symmetry during coherent transport in disordered media

Kilian Müller[1], Jérémie Richard[1], Valentin Volchkov[1], Vincent Denechaud[1], Tobias Micklitz[2], Alexander Altland[3], Cord Müller[4], Philippe Bouyer[5], Alain Aspect[1], Vincent Josse[1]

1. Laboratoire Charles Fabry UMR 8501, Institut d'Optique, CNRS, Univ. Paris Sud 11, 2 Avenue Augustin Fresnel, 91127 Palaiseau cedex, France

2. Dahlem Center for Complex Quantum Systems and Institut für Theoretische Physik, Freie Universität Berlin, 14195 Berlin, Germany

3. Institut für Theoretische Physik, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany

4. Department of Physics, University of Konstanz, 78457 Konstanz, Germany

5. Laboratoire Photonique, Numérique et Nanosciences - LP2N Université Bordeaux - IOGS - CNRS: UMR 5298, Talence, France

Coherent transport in disordered media has been a thriving topic for many decades. Started with the seminal paper by Anderson in 1958, introducing the possiblity of strong localization of waves, the interest is still alive nowadays as open questions remain. In the last years our group was able to observe Anderson Localisation (in 1D and 3D) and Coherent Backscattering (CBS) with ultracold atoms, allowing to study these phenomena in a precise way. In particular CBS, a very first manifestation of coherence in disordered media, relies on the time-reversability of the wave propagation. Here we show our latest experimental results where we deliberately break this symmetry in a precise way, enabling us to observe the destruction, and a short revival of the coherent signal when time reversal symmetry is briefly reestablished.

Superexchange Mediated Dynamics of Anti-Feromagnetic Order in an 2D Optical Lattice

S. B. Koller, R. Brown, B. Wyllie, E. A. Goldschmidt, D. G. Norris, M. Foss-Feig, J. V. Porto

1. Joint Quantum Institute, NIST and the University of Maryland, Room 2207 Computer and Space Sciences Building, College Park, MD 20742

We study experimentally the non-equilibrium dynamics of a 2D antiferromagnetic (AF) initial state in an optical lattice with one atom per site. We observe the decay of the staggered magnetization after a quench from a deep lattice to a shallow lattice, above the Mott insulator transition. In addition to final lattice depth, we vary a checkerboard like, state-independent energy offset. Over a range of lattice depths and staggered tilts we observe two decay time scales, a fast one of the order direct tunneling and a slower one of the order of a tilt-modified superexchange. Number dependence of the AF order decay is indicative of many body effects. In the presence of sufficiently staggered tilt, the fast tunneling is suppressed and our system is expected to be described by the Heisenberg Hamiltonian for unit filling. Our experiment is an ideal platform for studying many-body dynamics of states far from equilibrium.

Optimally Shaped Gates for Trapped Ion Chains

Taeyoung Choi, Shantanu Debnath, T. Andrew Manning, Caroline Figgat, Chris Monroe

1. Joint Quantum Institute and Department of Physics, University of Maryland, College Park, MD 20742
and National Institute of Standards and Technology

Scalable entanglement in trapped ion system is complicated by the multiple collective modes of motion [1]. We perform high fidelity and programmable multipartite entanglement by coupling all transverse modes of motion using optimal laser pulse shaping in a chain of five Yb+ qubits [2]. A focused mode-locked laser beam optically addresses subsets of qubits to perform entangling XX gates on any pairs of adjacent qubits. Pulse shaping by modulating the amplitude and phase of the laser can drive high fidelity gates for certain pulse solutions that are relatively insensitive to detuning errors and fluctuations. Using the pulse shaping, the individual addressing, and ion shuttling, we create tripartite entangled GHZ states in programmable approach. The optimally engineered pulse shapes coupling to multiple modes scale well for large qubit registers by keeping gate times short.

This work is supported by grants from the U.S. Army Research Office with funding from the DARPA OLE program, IARPA, and the MURI program; and the NSF Physics Frontier Center at JQI.

References

[1] S.-L. Zhu et al., Europhys. Lett, 73, 485 (2006).
[2] T. Choi et al., Phy. Rev. Lett, 112, 190502 (2014).

Quantum Simulation Tu-043

Quench dynamics in ion chains with variable-range interactions

Anton Buyskikh[1], Andrew Daley[1, 2], Johannes Schachenmayer[3], Benjamin Lanyon[4], Christian Roos[4]

1. University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
2. University of Strathclyde, Glasgow G4 0NG, UK
3. JILA, Boulder, Colorado 80309, USA
4. University of Innsbruck, 6020 Innsbruck, Austria

We study theoretically the non-equilibrium dynamics of one-dimensional chains of ions confined in linear traps. By coupling spin states of ions with collective phonon modes it is possible to tailor interactions along the chain so that their decay in space can be tuned in a wide range. Starting from a selection of initial states, we explore the dynamics of the system after the interactions are suddenly turned on, in particular focussing on the growth of bipartite entanglement in the chain and behavior of reduced density matrices. These can be obtained in experiments for small sub-chains via quantum state tomography. Following on from previous studies in which it was observed that the qualitative behaviour of the system differs for long and short range interactions, we investigate how the entanglement growth depends on the initial states and on the details of the Hamiltonian parameters.

Quantum Simulation and Many-Body Physics with 2D Ion Crystals in a Penning Trap

Justin Bohnet[1], Brian Sawyer[1], Joseph Britton[1], John Bollinger[1]

1. Ion Storage Group, National Institute of Standards and Technology, Boulder, CO

Quantum simulations promise to reveal new materials and phenomena for experimental study, but few systems have demonstrated the capability to control ensembles in which quantum effects cannot be directly computed. We report on new experiments characterizing a system of hundreds ^{9}Be+ ions that form 2D crystals in a Penning trap and can be used as a platform for incalculable quantum simulations. The ^{9}Be+ valence electron spins can be coupled using an effective Ising interaction with a tunable strength and range, coupling tens to hundreds of spins. We characterize the new experimental apparatus using the ion crystal stability, the spin-spin coupling strength, and the coherence time of the ensemble. Furthermore, we report on efforts to bench-mark quantum effects of the spin-spin coupling using a spin-squeezing witness, laying the foundation for future experiments including observation of entanglement dynamics under the quantum Ising Hamiltonian, high efficiency molecular spectroscopy, and studies of quantum thermalization.

Tunable spin-spin interactions and entanglement of ions in separate wells

Andrew Wilson[1], Yves Colombe[1], Kenton Brown[2], Emanuel Knill[1], Dietrich Leibfried[1], David Wineland[1]

1. *National Institute of Standards & Technology, 325 Broadway, Boulder CO, 80305, USA*
2. *Georgia Tech Research Institute, 400 10th Street, N.W., Atlanta GA 30332, USA*

Quantum simulation [1,2] may provide an understanding of the many quantum systems which cannot be modeled using classical computers. Despite impressive progress [3-5], a major challenge is the implementation of scalable devices. In this regard, individual ions trapped in separate tunable potential wells are promising [6-8]. Here we implement the basic features of this approach and demonstrate deterministic tuning of the Coulomb interaction between two ions, independently controlling their local wells. The scheme is suitable for emulating a range of spin-spin interactions, but to characterize the performance of our setup we select one that entangles the internal states of the two ions with 0.82(1) fidelity. Extension of this building-block to a 2D-network, which ion-trap micro-fabrication processes enable [9], may provide a new quantum simulator architecture with broad flexibility in designing and scaling the arrangement of ions and their mutual interactions. To perform useful quantum simulations an array of tens of ions might be sufficient [4,10,11].

References

[1] Feynman, R. P., Simulating physics with computers. Int. J. Theor. Phys. 21, 467-488 (1982).

[2] Lloyd, S., Universal quantum simulators. Science 273, 1073-1078 (1996).

[3] Ladd, T. D. et al., Quantum computers. Nature 464, 45-53 (2010).

[4] Georgescu I. M., Ashhab, S. & Nori F., Quantum simulation. Rev. Mod. Phys. 86, 153-185 (2014).

[5] Blatt, R. & Roos, C. F., Quantum simulations with trapped ions. Nature Phys. 8, 277-284 (2012).

[6] Chiaverini, J. & Lybarger, W. E., Laserless trapped-ion quantum simulations without spontaneous scattering using microtrap arrays. Phys. Rev. A 77, 022324 (2008).

[7] Schmied, R., Wesenberg, J. H. & Leibfried, D., Optimal surface-electrode trap lattices for quantum simulation with trapped ions. Phys. Rev. Lett. 102, 233002 (2009).

[8] Shi, T. & Cirac, J. I., Topological phenomena in trapped-ion systems. Phys. Rev. A 87, 013606 (2013).

[9] Seidelin, S. et al., Microfabricated surface-electrode ion trap for scalable quantum information processing. Phys. Rev. Lett. 96, 253003 (2006).

[10] Friedenauer, A., Schmitz, H., Glueckert, J. T., Porras, D. & Schaetz, T., Simulating a quantum magnet with trapped ions. Nature Phys. 4, 757-761 (2008).

[11] Nielsen, A. E. B., Sierra, G. & Cirac, J. I., Local models of fractional quantum hall local models of fractional quantum hall states in lattices and physical implementation. Nature Commun. 4, 2864 (2013).

Experimental Developments towards studying Quantum Dynamics in Trapped Ions

Debashis De Munshi[1], Riadh Rebhi[1], Manas Mukherjee[1]

1. Center for Quantum Technologies, National University of Singapore

In this work, we present experimental developments towards studying the quantum dynamics in trapped ions. Our focus will be on the traditional linear trap design modified such that it allows us to dynamically evolve the the trap Hamiltonian by electric fields only. Commencing with a brief introduction to the theoretical framework for the possible observation of geometric phases as well as non-Abelian to Abelian transitions, we will show the experimental development towards realizing it.

Quantum Simulation Tu-047

Implementing scaleable remote ion-photon entanglement

Richard Graham[1], Zichao Zhou[1], Chen-Kuan Chou[1], Thomas Noel[1], Carolyn Auchter[1], Boris Blinov[1]

1. University of Washington

Recent work in quantum information processing with trapped ions has demonstrated many of the elements required for realizing a quantum computer with hundreds of qubits distributed across multiple connected ion traps. Efficient collection and fiber coupling of fluorescence light from trapped ions is critical for fast qubit state detection and for generating the remote entanglement of ions necessary for such a quantum computer. We are currently working with barium ions and are investigating two possible approaches to collecting 493 nm fluorescence; custom large area external aspheric optics and trapping ions at the focus of a custom parabolic mirror.

Preparation of High NOON State of Phonon in a Trapped-ion System

Junhua Zhang[1], Kihwan Kim[1]

1. Center for Quantum Information, Tsinghua University

Highly entangled NOON states have a wide range of potential applications in quantum communication, quantum information processing and quantum precision measurement. Here we realize the NOON state with two motional modes of a single ion in a standard Paul trap. We develop a composite-pulse scheme of stimulated Raman transitions to prepare arbitrary size of NOON state in the trapped-ion system and verify its fidelity by observing the parity oscillation of the state depending on the measurement basis.

A microwave trap for sympathetic cooling of polar molecules

Devin Dunseith, Stefan Truppe, Rich Hendricks, Ben Sauer, Ed Hinds, Mike Tarbutt

1. The Centre for Cold Matter, Imperial College London

In the Centre for Cold Matter, we have been developing techniques to cool molecules into the microkelvin regime. One such method is sympathetic cooling, using ultracold atoms as a refrigerant to cool molecules. Previous work has suggested that atoms and molecules can be trapped in the antinode of a Fabry-Perot microwave cavity [1][2].

The most efficient way to couple microwave power into this cavity is from a rectangular waveguide, via a small coupling hole in one mirror. We have developed an analytical model that helps us understand this coupling mechanism, and gives us a good idea of how the size of the coupling hole affects both the coupling of the cavity and the cavity's finesse. We carried out finite-difference time-domain simulations and performed experiments on a prototype cavity to verify this model.

We have now designed and built this trap for operation under ultra-high vacuum, with the ability to cool the cavity mirrors to 77 K and couple in up to 2 kW of microwave power. This will allow us to trap molecules with a moderate dipole moment at temperatures of hundreds of millikelvin, as well as atoms at a few millikelvin.

We will present our work thus far in creating the microwave trap - the results of our model, our understanding of the mode in the cavity and how best to create the deep trap we will need to sympathetically cool molecules. We will also present our first results demonstrating trapping of lithium atoms in the microwave trap

References

[1] D. DeMille, D. R. Glenn and J. Petricka, Eur. Phys. J. D 31, 375 (2004)

[2] S. K. Tokunaga, W. Skomorowski, P. S. Zuchowski, R. Moszynski, J. M. Hutson, E. A. Hinds and M. R. Tarbutt, Eur. Phys. J. D 65, 141 (2011)

Towards a Three Dimensional Magneto-Optical Trap for Diatomic Molecules

Matthew T. Hummon[1], Mark Yeo[1], Alejandra Collopy[1], Boerge Hemmerling[2, 3], Eunmi Chae[2, 3], Garrett Drayna[2, 3], Aakash Ravi[2, 3], Nicholas R. Hutzler[2, 3], John M. Doyle[2, 3], Jun Ye[1]

1. JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder 80309, CO, USA
2. Department of Physics, Harvard University, Cambridge, MA 02138, USA
3. Harvard-MIT Center for Ultracold Atoms, Cambridge, MA 02138, USA

We present progress towards a three-dimensional magneto-optical trap (MOT) for diatomic molecules. A dual-stage cryogenic buffer gas beam source produces a cold, slow beam of YO molecules with a mean forward velocity of 70 m/s. White light slowing will be used to decelerate a portion of the YO beam to within the MOT capture velocity, about 10 m/s. The AC magnetic field for the MOT is generated with in-vacuum magnetic coils with a resonant frequency of 5 MHz. The modulation of both the magnetic field and optical polarization of the MOT beams provides for rapid remixing of the Zeeman states in YO, which is essential to maintain the MOT trapping force given by the electronic radiative process.

A cryogenic buffer-gas BaH beam for molecular laser cooling and ultracold fragmentation

Marco G. Tarallo[1], Geoffrey Iwata[1], Florian Apfelbeck[1], Bart McGuyer[1], Mickey McDonald[1], Tanya Zelevinsky[1]

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

We report on the current status of a new experiment on cooling and trapping barium monohydride (BaH) diatomic molecules. This molecule is a good candidate for laser cooling, and is attractive for future studies of ultracold fragmentation due to the large mass ratio of its constituent atoms. We describe the plans for the cryogenic beam apparatus and the initial spectroscopy of thermal BaH molecules produced by laser ablation. We also discuss different strategies to perform laser cooling of BaH.

Photoassociation spectroscopy of RbYb in a conservative trap

Axel Goerlitz[1], Cristian Bruni[1]

1. *University of Duesseldorf*

The creation of ultracold heteronuclear molecules with anisotropic electric dipole interaction is one of the prominent goals in ultracold atom physics. While the widely used bialkalis possess no magnetic moment in the electronic ground state, RbYb is paramagnetic and thus has an additional degree of freedom.

Here we report on our most recent step towards the creation of ultracold RbYb ground state molecules namely photoassociation of RbYb in a conservative trap. In a newly designed trap consisting of a magnetic trap for Rb and an optical trap near the intercombination line for Yb we perform one-photon spectrosocopy on weakly-bound vibrational levels of excited Rb*Yb molecules. This combines our previous studies on photoassociation spectroscopy of RbYb in a magnetooptical trap [1,2] and simultaneous conservative trapping of the two species [3].

References

[1] N. Nemitz et al., Phys. Rev. A 79, 061403(R) (2009) [2] M. Borkowski et al., Phys. Rev. A 88, 052708 (2013) [3] F. Baumer et al., Phys. Rev. A 83, 040702(R) (2011)

Ultracold Mixtures and Molecules Tu-053

Continuous formation of rovibronic ground state RbCs molecules via photoassociation

Toshihiko Shimasaki[1], Michael Bellos[1], Colin Bruzewicz[1, 2], Zack Lasner[1], David DeMille[1]

1. *Department of Physics, Yale University*
2. *Current affiliation: Lincoln Laboratory, MIT*

We recently demonstrated the direct formation of vibronic ground state RbCs molecules via short-range photoassociation (PA) [1]. We identified the PA resonances as vibrational levels in the $(2)^3\Pi_{0+}$ potential by comparing the resonance locations with spectroscopic data. We also obtained satisfactory agreement between experimental molecule production rates and Franck-Condon factor calculations, and devised a simple method for analyzing rotational line strengths in PA spectra. In this poster, we will report on recent progress in populating the rovibrational ground state X(v=0, J=0) formed following PA, which was confirmed by depletion spectroscopy with a narrow-band CW diode laser. This is an important step to verify the feasibility of our future prospects to accumulate a large sample of ground-state RbCs molecules by continuous PA, and to purify this sample by collisional “scrubbing” of rovibrational excited states.

References

[1] C.D. Bruzewicz et al., New J. Phys. 16, 023018 (2014)

Probing evanescent field coupling between laser-cooled ^{87}Rb atoms and the fundamental and higher order modes of an optical nanofiber.

Vandna Gokhroo[1], Ravi Kumar[1, 2], Aili Maimaiti [1, 2], Kieran Deasy[1], Síle Nic Chormaic[1]

1. Okinawa Institute of Science and Technology, 1919-1 Tancha, Okinawa, Japan
2. Physics Department, University College Cork, Cork, Ireland

Optical nanofibers (ONFs), with subwavelength diameters, have a strong evanescent field around them. When an ONF is combined with a cold atom setup, the surrounding cold atoms interact with the different modes present in the fiber via evanescent field coupling. To date, most experimental studies have focused on ONFs that support only the fundamental mode. ONFs supporting higher order modes have advantages since they have a larger diameter - thereby being more robust - and the evanescent field extends further from the fiber surface - leading to light coupling with more atoms.

Motivated by the work of Masaloav and Minogin [1] we studied the fluorescence emission from, and absorption coupling of, cold atoms to an ONF supporting the fundamental (HE_{11}) and the first group of higher modes (TE_{01}, TM_{01}, HE_{21}). We observed that fluorescent light from the atoms coupling in to the nanofiber through the waist has ~ 6 times higher pumping rate for the higher-order fiber modes compared to the fundamental mode. We also demonstrated that there is more absorption of the light by atoms when probe light is guided in the higher order modes rather than in the fundamental mode [2]. These results will be useful in implementing higher order modes through ONFs for mode interference-based atom trapping schemes.

References

[1] A. V. Masalov and V. G. Minogin, Laser Phys. Lett. 10, 075203 (2013).
[2] R. Kumar, V. Gokhroo, K. Deasy, A. Maimaiti, M. C. Frawley, C Phelan and S. Nic Chormaic, arXiv:1311.6860

A two-frequency ion trap confining ions with different charge-to-mass ratios

Dimitris Trypogeorgos[1], Christopher Foot[1]

1. Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, UK

We describe the theory of two-frequency operation of an ion trap [1] and solve the equations of motion for two species of ions with molecular mass, charge: M_A,+1 and M_B,+33 respectively, where M_A = 138 amu is an isotope of barium and $M_B = 1.4\ 10^6$ amu, e.g., a large protein or molecular complex. The quadrupole electric field is created by RF radiation with angular frequencies ω_1 and ω_2 with $\omega_2 = 100\omega_1$. We obtain a superposition of two almost independent Paul traps whose centres can be made coincident or moved apart, while the effective spring constants can be adjusted to be the same for both species which allows for efficient sympathetic cooling. This approach can be extended to ions with more similar masses to improve the fidelity of quantum logic operations. Manipulation of the orientation of larger particles along the electric field of the trap is also considered.

References

[1] D. Trypogeorgos and C. Foot, arXiv:1310.6294 (2013)

Ion trap surface cleaning and microwave-driven gates

David Allcock[1], Daniel Slichter[1], Dustin Hite[1], Andrew Wilson[1], Robert Jordens[1], Kyle McKay[1], David Pappas[1], Dietrich Leibfried[1], David Wineland[1]

1. Time and Frequency Division, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

We present our current progress towards performing quantum logic gates on trapped-ion qubits at fidelities suitable for fault-tolerant quantum computing. Our two main technical goals are eliminating the so-called ‘anomalous heating’ of ion motion and improved near-field microwave control of hyperfine ‘clock’ qubits. The effort to reduce the anomalous heating, which limits the fidelity of gates in very small ion traps, is focussed on surface treatment methods to remove contaminants from the trap electrodes. We have shown that argon-ion bombardment can reduce the anomalous heating by a factor of 100 [1], and will report on testing other cleaning methods. Our near-field microwave control work will build on previous work on high fidelity single qubit gates [2], single qubit addressing [3] and two-qubit gates [4].

References

[1] D. Hite et al. PRL 109, 103001 (2012)
[2] K. Brown et al. PRA 84, 030303 (2011)
[3] U. Warring et al. PRL 110, 173002 (2013)
[4] C. Ospelkaus et al. Nature 476, 181 (2011)

Development of Microfabricated 2-D Ion Trap for Quantum Information Processing

Taehyun Kim[1], Seokjun Hong[2], Minjae Lee[2], Hongjin Cheon[2], Jun Sik Ahn[1], Min Hyung Kim[1], Dong-Il “Dan” Cho[2]

1. *Quantum Technology Lab, SK Telecom, Seongnam-si, Gyeonggi-do, 463-784, Republic of Korea*
2. *ASRI/ISRC and Department of Electrical and Computer Engineering, Seoul National University, Seoul, 151-744, Republic of Korea*

We present a microfabricated ion trap to implement a scalable platform for quantum repeater and quantum computing application. To prevent high-voltage breakdown, we used a 14-μm thick PECVD-deposited SiO_2 dielectric layer which induces less residual stress as compared to the conventionally used tetraethyl orthosilicate (TEOS) films. The trap has one set of RF electrodes, 42 sets of DC control electrodes and slit opening dimensions of 2.3mm x 0.1mm. The RF null is located about 82μm above the trap surface and with the applied RF voltage of 320V peak-to-peak at 25.5MHz, we can trap up to six $^{174}Yb^+$ ions and three $^{171}Yb^+$ ions. A lifetime of more than 10 hours has been observed with Doppler cooling, and we can shuttle trapped ions along the trap axis. We will report the characterization result of this trap and our working progress in implementation of quantum repeater.

Grating chips for quantum technologies

Erling Riis[1], James McGilligan[1], Paul Griffin[1], Aidan Arnold[1]

1. *Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, UK*

Laser cooled atomic samples have revolutionised atomic physics and are key to new quantum technologies such as frequency metrology and novel atom-based sensors. However, the setups are typically complex and bulky largely due to the multitude of laser beams required.

Micro-fabricated diffractive optical elements [1] can greatly facilitate the miniaturisation of magneto-optical traps (MOTs) for use in ultra-cold atom technology. Such an element can transform a single circularly-polarised input beam into all required beams for an intensity-balanced MOT [1]. This has enabled the realisation of chip-based and sub-Doppler cooled atomic samples, which could subsequently be loaded into a magnetic trap.

Here we present this and more of our latest results on grating-based optical molasses including precise optical characterisation of several new grating designs and an investigation of the phase-space properties in the MOT.

References

[1] C. C. Nshii et al., Nature Nanotechnology 8, 321 (2013).

Double-Loop Microtrap Array for Ultracold Atoms

Bin Jian, William van Wijngaarden

1. Physics Department, York University

A novel kind of magnetic microtrap has been demonstrated for ultracold neutral atoms [1,2]. It consists of two concentric current loops having radii r_1 and r_2. A magnetic field minimum is generated along the axis of the loops if oppositely oriented currents flow through the loops. Selecting $r_2/r_1=2.2$ maximizes the restoring force to the trap center. The strength and position of the microtrap relative to the atom chip surface can be precisely adjusted by applying an external bias magnetic field. A microtrap array can be formed by linking individual microtraps in series. A linear array of 3 microtraps having r_1 = 300 microns, was loaded with more than 10 ^{587}Rb atoms using three different methods: 1) from a transported quadrupole magnetic trap, 2) directly from a mirror MOT and 3) from an optical dipole trap.

References

[1] B. Jian & W. A. van Wijngaarden, Journal Optical Society of America B, 30, No. 2, 238-243 (2013).
[2] B. Jian & W. A. van Wijngaarden, Appl. Physics B:Lasers & Optics. DOI 10.1007/s00340-013-5573-4 (2013).

Sub-micron magnetic lattices for Quantum Simulation

Arthur La Rooij[1], Lara Torralbo-Campo[1], Maarten Soudijn[1], Julian Naber[1], Ben van Linden van den Heuvell[1], Robert Spreeuw[1]

1. van der Waals- Zeeman Institute, University of Amsterdam

We use nano-lithography techniques to create lattice potentials in permanent magnetic films at atom chips. These lattices can be created over a large range of length scales and are used to trap mesoscopic clouds of ultracold atoms [1]. We are downscaling the lattice spacing from our current 10um to much smaller lattices for a new series of experiments [2]. On these new atom chips we created lattices with lattice spacing varying from 250nm up to 5um on the same chip. The 50nm thick monocrystaline FePt films are grown with MBE and are then patterned by e-beam lithography to obtain structures with a 20nm resolution. This technique can extend the range of length scales of optical lattices to both smaller and larger sizes, and can be used to study degenerate gases in new regimes and environments. Geometrical interfaces have been constructed to study the role of disorder, frustration and dimensionality.

References

[1] V.Y.F Leung, D.R.M Pijn, H.Schlatter, L.Torralbo-Campo, A. La Rooij, G.B. Mulder, J.Naber, M.L. Soudijn, A. Tauschinsky, C. Abarbanel, B, Hadad, E. Golan, R. Folman, R.J.C. Spreeuw, Review of Sciencentific Instruments 88, 053102 (2014).
[2] V.Y.F. Leung, A. Tauschinsky, N. J. van Druten, R. J. C. Spreeuw, Quantum Inf Process 10, 955-974 (2011)

Highly Efficient Free-Space Atom-Light Interface

Martin Fischer[1, 2], Marianne Bader[1, 2], Simon Heugel[1, 2], Markus Sondermann[1, 2], Gerd Leuchs[1, 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 present a setup capable of transforming a paraxial Gaussian-beam into a spherical linear-dipole wave. This is accomplished by focusing a radially polarized Laguerre-Gaussian beam with a parabolic mirror covering 94% of the solid angle relevant for a linear dipole. This mode is interfaced to an ion at the focus of the parabolic mirror, providing an ideal probe for the created mode. Reducing our focusing geometry to half solid-angle enables us to monitor the upper-level population of the driven transition by measuring the light scattered by the ion into the complementary solid angle part. By varying the incident power we determine the coupling efficiency to the linear dipole to be 27%. Our setup demonstrates the highest efficiency for coupling between light and a single emitter in free space reported so far. Extrapolating from half to full solid-angle yields an efficiency of 54%.

Hybrid trap for atoms, ions and molecules built within a Fabry-Perot cavity

Tridib Ray[1], S. Jyothi[1], N. Bhargava Ram[1], S. A. Rangwala[1]

1. Raman Research Institute, Sadashivanagar, Bangalore-560080, India

The study of two, few and many particle systems, where the interactions are mediated by central potentials ranging from $1/r$ to $1/r^6$ can be realized in cold, dilute gas mixtures of ions, atoms and molecules. To enable these studies in a comprehensive way, we have developed an apparatus capable cooling and trapping ions and ultracold atoms and creating and trapping ultracold molecules[1]. Our scheme allows the trapped overlap of specific numbers of ions, atoms and molecules, in prepared internal states, so that interactions of any combination can be studied. An important feature of the apparatus is that the center of the trapping region lies on the axis of a Fabry-Perot cavity, enabling resonant interrogation of the species within[2]. We present this experiment and the initial results[1],[2],[3] with this hybrid apparatus which demonstrate the capabilities of this system and discuss future prospects.

References

[1] S Jyothi, Tridib Ray, N Bhargava Ram, S A Rangwala, arXiv: 1312.2715 (2013)
[2] Tridib Ray, A Sharma, S Jyothi, S A Rangwala, Phys Rev A, 87(3) 033832 (2013)
[3] Tridib Ray, S Jyothi, N Bhargava Ram, S A Rangwala, Appl Phys B, 114 (1-2), 267 (2014)

Spontaneous coherence of magnons in spin-polarized atomic hydrogen gas

Otto Vainio[1], Lauri Lehtonen[1], Janne Ahokas[1], Jarno Järvinen[1], Sergey Sheludyakov[1], Denis Zvezdov[1, 2], Kalle-Antti Suominen[1], Sergey Vasiliev[1]

1. *Department of Physics and Astronomy, University of Turku, 20014 Turku, Finland*
2. *Kazan Federal University, 420008, 18 Kremlyovskaya St, Kazan, Russia*

A macroscopic occupation of the ground state and long-range correlations are the hallmarks of Bose-Einstein condensation. The phenomenon has also been observed in systems of wave-like excitations such as photons, excitons, and spin waves (magnons). Spin waves in cold gases are propagating perturbations of spins, i.e. travelling fluctuations of the macroscopic magnetization. The propagation results from the cumulative effect of the identical spin rotation effect due to exchange interaction. In spin-polarized atomic hydrogen gas, magnons can be trapped and controlled by magnetic forces in a manner similar to ordinary atoms [1]. We demonstrate confinement of magnons in magnetic traps of distinct geometries. We show that at a critical density of H gas magnons accumulate in the ground state and exhibit long-term coherence, profoundly changing the electron spin resonance spectra. We interpret these effects as signs of spontaneous coherence and argue for an explanation in terms of BEC of magnons.

References

[1] O. Vainio, J. Ahokas, S. Novotny, S. Sheludyakov, D. Zvezdov, K.-A. Suominen and S. Vasiliev, PRL 108, 185304 (2012)

Modular Quantum Systems with Photons and Phonons

Grahame Vittorini, David Hucul, Ismail V. Inlek, Clayton Crocker, Chris Monroe

1. Joint Quantum Institute, University of Maryland Department of Physics and National Institute of Standards and Technology

Distributed, modular systems for quantum information processing require the use of both stationary and flying qubits and no single physical qubit type currently fills both roles. One proposal uses trapped ions as stationary qubits due to their long coherence times and robust control and photons as flying qubits that allow entanglement of stationary qubits in separate modules [1]. We have demonstrated a basic version of this ion-photon system consisting of two modules [2]. By utilizing photonic and phononic buses, we generate entanglement both between two qubits within one module and a second qubit stored in the other. Most importantly, intramodular entanglement generation occurs more quickly than coherence of the entangled state is lost. This feat has only been accomplished in this ion-photon system and indicates that scaling of this system is achievable. Additionally, we discuss control and stability of intramodular [3] and intermodular phases.

References

[1] Monroe, C. et al., Phys Rev. A 89, 022317 (2014).
[2] Hucul, D. et al., arXiv:1403.3696 (2014).
[3] Inlek, I.V. et al., arXiv:1405.5207 (2014).

Controlled photon emission of two ions in a cavity as enhanced quantum interface

B. Casabone[1], K. Friebe[1], B. Brandstätter[1], K. Schüppert[1], R. Blatt[1, 2], T. E. Northup[1]

1. Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
2. Institut für Quantenoptik und Quanteninformation, Osterreichische Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria

Sub- and superradiance are widely studied fundamental effects in quantum optics. We generate sub- and superradiant states of a two-ion crystal coupled to an optical cavity. The ions interact with the cavity via a cavity-mediated Raman transition. In the context of quantum information, the transfer of a qubit state encoded in a single ion onto a single photon within an optical cavity has been recently shown. Here, we encode the qubit state in a superradiant state of a two-ion crystal before performing the transfer. We show an overall enhancement in the process fidelity and efficiency of the mapping process compared to the single-ion case. The results are a proof of principle of how cooperative effects can be utilized to improve the performance of a quantum node of a quantum network.

Transverse electron momentum distribution for arbitrary polarization state of the ionizing laser pulse

Igor Ivanov[1], Anatoli Kheifets[1]

1. Research School of Physical Sciences, The Australian National University

We study evolution of the distribution of electron momenta in the direction perpendicular to the polarization plane with the change of the ellipticity parameter of the driving laser pulse. We show, that the distribution gradually changes from the singular cusp-like distribution for the close to linear polarization to the smooth gaussian-like structure for the close to circular polarization states. In the latter case, when the ellipticity parameter is close to one, the strong field approximation [1] formula for the transverse momentum distribution become quantitatively correct.

References

[1] L. V. Keldysh, Sov. Phys. -JETP. 20, 1307 (1965).

Two-dimensional absorption spectroscopy with attosecond XUV light: Unraveling bound-state electron dynamics in strong laser fields.

Alexander Blaettermann[1], Christian Ott[1], Andreas Kaldun[1], Thomas Ding[1], Thomas Pfeifer[1]

1. Max Planck Institute of Nuclear Physics, Heidelberg (Germany)

We demonstrate a two-dimensional spectroscopy method to observe dynamics of atomic bound states in strong laser fields. The approach allows to separate different pathways of light-matter interaction, *e.g.* non-resonant interactions and resonant coupling among states, and thus enables us to analyze each type of interaction individually. Furthermore, it is possible to extract amplitude and phase modifications imprinted on a quantum system as it interacts with an ultrashort laser pulse.

The method is based on Fourier analysis of the time-resolved absorption spectrum of an ultrashort excitation pulse, in which the information about the system's evolution is encoded. The underlying analytical framework predicts the building blocks of the spectra, and reveals how amplitude and phase information can be directly retrieved from the experimental spectrum.

We experimentally study the transient coupling, introduced by interaction with a few-cycle near-infrared laser pulse, of doubly-excited states in helium, which are excited by attosecond-pulsed extreme ultraviolet light.

Low-energy enhanced multiphoton above-threshold ionization in a strong laser field of mid-infrared wavelength

Vladimir Usachenko[1], Pavel Pyak[2]

1. *Institute of Applied Physics, National University of Uzbekistan, Tashkent, 100174, Uzbekistan*
2. *Physics Department, National University of Uzbekistan, Tashkent, 100174, Uzbekistan*

We report about the results of our study of strong-field (multiphoton) above-threshold ionization (ATI) in laser-irradiated atomic species (*Ar*, *Xe*) under conditions of recent experiments [1, 2] observing an unexpected characteristic spike-like low-energy structure in photoelectron energy distribution (PED), which becomes prominent using mid-infrared laser wavelengths ($\lambda > 1.0$ μm) corresponding to intermediate values of the *Keldysh parameter* ($\gamma \leq 1$). The problem is addressed theoretically within the *velocity-gauge* formulation of *strong-field approximation* (SFA) [3] complemented with the *density-functional-theory* (DFT) applied for numerical composition of initial (laser-free) atomic state using the routines of GAUSSIAN-03 code [4]. Our DFt_SFA calculation results clearly demonstrate a remarkably enhanced ionization rate in low-energy domain of PED and fairly well reproduce their low-energy structure and its intensity-dependent behavior observed in relevant experiments (particularly, a noticeable energy shift of maximum ionization rate to higher energies under increasing the laser peak intensity).

References

[1] C.I. Blaga et al., Nat. Phys. 5, 335 (2009).
[2] W. Quan et al., Phys. Rev. Lett. 103, 093001 (2009).
[3] V.I. Usachenko et al., Phys. Rev. A79, 023415 (2009).
[4] M.J. Frisch and J. A. Pople Gaussian-03, Revision A.1 (Gaussian, Inc., Pittsburgh, PA, 2003).

Pressure optimization of high harmonic generation with argon gas jet

Muhammed Sayraç[1], Alexandre A. Kolomenskii[1], James Strohaber[2], Yakup Boran[1], Gamze Kaya[1], Necati Kaya[1], Hans A. Schuessler[1]

1. *Department of Physics & Astronomy, Texas A&M University, College Station TX 77843-4242, USA*
2. *Department of Physics, Florida A&M University, Tallahassee, Florida 32307, USA*

High harmonic generation (HHG) in a gas jet depends on pressure due to density changes, variation of the matching conditions and absorption. In this work we experimentally studied the pressure dependence of the output of high harmonics at HHG process in Ar gas at moderate peak laser intensities in the interaction region ~$1.5\text{x}10^{14}$W/cm^2. To enable measurements in a broad range of pressures we employed an additional chamber enclosing the gas jet with differential pumping. By varying the Ar gas jet pressure within the range p~0.05-3bar, we observed the maximum HHs output at p~0.5-1bar. Compared to the case without the enclosing chamber, we achieved the HHG enhancement up to four times and extension of the cutoff by two more harmonics from 27th to 29th order.

This work was supported by the by the Robert A. Welch Foundation grant No. A1546 and the Qatar Foundation under the grant NPRP 5-994-1–172.

Effect of different transverse modes of femtosecond pulses on filament propagation

Necati Kaya[1], Gamze Kaya[1], Muhammed Sayraç[1], James Strohaber[1, 2], Alexandre Kolomenski[1], Hans Schuessler[1]

1. *Department of Physics, Texas A&M University, College Station, TX 77843-4242, USA*
2. *Department of Physics, Florida A&M University, Tallahassee, Florida 32307, USA*

We experimentally studied femtosecond pulse filamentation and propagation in water for Gaussian, Laguerre-Gaussian, and Bessel beams. Three different transverse modes were created from an initial Gaussian beam by using a computer generated hologram technique. We found that the propagation length of the filament produced by the Bessel incident beam was longer than that for the other transverse modes under the conditions of the same peak intensity, pulse duration, and the size of the central part of the beam. We performed for a Bessel-type beam a more detailed study of the filament length on the number of radial lobes. This length increased with the number of lobes, which implies that they serve as an energy reservoir for the filament formed by the central intensity peak.

This work was supported by the by the Robert A. Welch Foundation grant No. A1546 and the Qatar Foundation under the grant NPRP 6-465-1-091.

Reduced-Density-Matrix Description for Pump-Probe Optical Phenomena in Moving Many-Electron Atomic Systems

Verne Jacobs[1]

1. *Naval Research Laboratory*

Linear and non-linear (especially coherent) electromagnetic interactions of moving many-electron atomic systems are investigated using a reduced-density-matrix description. Complimentary time-domain (equation-of-motion) and frequency-domain (resolvent-operator) formulations are self-consistently developed. The general non-perturbative and non-Markovian formulations provide a fundamental framework for the systematic introduction of the standard Born (lowest-order-perturbation) and Markov (short-memory-time) approximations. The macroscopic electromagnetic response is described semi-classically, employing a perturbation expansion of the reduced-density operator in powers of the classical electromagnetic field. We obtain compact Liouville-space operator expressions for the linear and general (n’th order) non-linear macroscopic electromagnetic-response tensors, which can be evaluated for a non-local and non-stationary optical medium. Binary atomic collisions and single-photon processes are incorporated as environmental interactions by means of a Liouville-space self-energy operator, for which the tetradic-matrix elements are explicitly evaluated in the isolated-line, lowest-order, and Markov approximations.

Effect of nuclear mass on carrier-envelope-phase controlled electron localization in dissociating molecules

Robert Sang[1, 3], Han Xu[1], Tian-Yu Xu[2], Feng He[2], Dave Kiepinski[1, 3]

1. *Centre for Quantum Dynamics and Australian Attosecond Science Facility, Griffith University, Nathan, QLD 4111, Australia*
2. *Key Laboratory for Laser Plasmas (Ministry of Education), and Department of Physics and Astronomy, SJTU, Shanghai 200240, People's Republic of China*
3. *ARC Centre of Excellence for Coherent X-Ray Science, Griffith University, Nathan, QLD 4111, Australia*

Coherent control of molecular fragmentation with few-cycle laser pulses of well-defined carrier-envelope phase (CEP) has become an active research topic in ultrafast science due to its potential application for control of chemical reactions[1-3]. We explore the effect of nuclear mass on the laser-driven electron localization process[4]. We dissociate a mixed H_2/D_2 target with intense, carrier-envelope-phase (CEP) stable 6 fs laser pulses and detect the products in a reaction microscope. We observe a very strong CEP-dependent asymmetry in proton/deuteron emission for low-KER dissociation channels. This asymmetry is much stronger for H_2 than for D_2 . We also observe a large CEP offset between the asymmetry spectra for H_2 and D_2. Our theoretical simulations, based on a one-dimensional two-channel model, agree very well with the asymmetry spectra, but fail to account properly for the phase difference between the two isotopes.

References

[1]. M. F. Kling et al., Science, 312, 246 (2006).
[2]. M. Kremer et al., Phys. Rev. Lett. 103 213003 (2009).
[3]. H. Xu, et al, New Journal of Physics, 15, 023034 (2013).
[4]. H. Xu, et al , Phys. Rev. A 89, 041403(R) (2014).

Quantum Information Tu-073

Quantum Secret Sharing Using Multi-Spatial-Mode Entangled Light

Travis Horrom[1], Prasoon Gupta[1], Ryan Glasser[1], Brian Anderson[1], Paul Lett[1]

1. Quantum Measurement Division, National Institute of Standards and Technology, and Joint Quantum Institute, NIST and the University of Maryland

With the advent of quantum cryptography it became possible for two parties to share a secret key that is mathematically provably secure against eavesdropping. A desirable extension of this concept is multi-user quantum secret sharing, in which a message or key is sent to multiple parties who must work together to access it. Here we demonstrate multi-party secret sharing by using a four-wave mixing process in atomic vapor to produce a multiple-spatial-mode continuous-variable entangled state of light. We generate random bit streams by performing quadrature measurements on spatially distinct modes of the light, and combine these bit streams to generate a key. Simultaneously, the entangled pairs of these modes are sent to different receivers who perform similar measurements. While the bit streams produced by the receivers individually are not correlated with the key, these parties can work together and combine their information to reconstruct the key.

Quantum Information Tu-074

Adiabatic state transformation in the presence of classical noise.

Guanglei Xu[1]

1. University of Pittsburgh

In adiabatic state transformations, the role of classical noise is still not well understood. For quantum simulated annealing, however, recently computed upper bounds[1] for the time cost with randomness introduced in each time step show a quadratic speed in the size of energy gaps up over upper bounds for adiabatic quantum computation. We study of classical noise in adiabatic state transformation by stochastic simulation (for coloured noise) and a master equation approach (for white noise), comparing the cost between the noisy Hamiltonian and the noise-free case. For particular parameter regimes, we find evidence that introducing specific types of noise could improve the final fidelity of state preparation for limited total time, both in in two-level systems, and in the transverse Ising model and Bose-Hubbard model in 1D.

References

[1] H. T. Chiang, G. Xu, and R. D. Somma, Phys. Rev. A 89, 012314

All optical quantum storage based on spatial chirp of the control field

Xiwen Zhang[1], Alexey Kalachev[2, 3], Olga Kocharovskaya[1]

1. Department of Physics and Astronomy and Institute for Quantum Studies, Texas A&M University, College Station, Texas 77843-4242, USA
2. Zavoisky Physical-Technical Institute of the Russian Academy of Sciences, Sibirsky Trakt 10/7, Kazan, 420029, Russia
3. Kazan Federal University, Kremlevskaya 18, Kazan, 420008, Russia

We suggest an all-optical quantum memory scheme which requires neither synchronization and temporal manipulation on the control field and medium nor the presence of the Stark or Zeeman effect in the atomic medium. The scheme is based on the off-resonant Raman interaction of a signal quantum field and a strong control field in a three-level atomic medium in the case, when the control field has a spatially varying frequency across the beam, called a spatial chirp. We show that the effect of such a spatial chirp is analogous to the effect of a controllable reversible inhomogeneous broadening (CRIB) of the atomic transition used in the gradient echo memory (GEM) scheme. We find that for the optimal conditions the proposed spatial-chirp memory scheme is capable of almost one hundred percent efficiency in the retrieval of the stored quantum signal. This scheme is also analogous to phase matching control (PMC) memory schemes [1-4].

References

[1] A. Kalachev and O. Kocharovskaya, Phys. Rev. A 83, 053849 (2011). [2] X. Zhang, A. Kalachev, Phys. Rev. A 87, 013811 (2013). [3] A. Kalachev and O. Kocharovskaya, Phys. Rev. A 88, 033846 (2013). [4] X. Zhang, A. Kalachev, P. Hemmer, M. Scully, O. Kocharovskaya, submitted to Laser Phys..

Rydberg Quantum Information using a Magnetic Film Atom Chip

L. Torralbo-Campo[1], M.L Soudijn[1], J.B. Naber[1], A.L. Rooij[1], H.B van Linden va den Heuvell[1],
R.J.C Spreeuw[1]

1. Van der Waals- Zeeman Institute / Institute of Physics, University of Amsterdam

We present our ongoing research with two-dimensional atomic ensembles in a lattice of Ioffe-Pritchard type microtraps arrays created by a patterned permanent-magnetic film atom chip [1]. We recently demonstrated the loading of ultracold ^{87}Rb atoms in 600 lattice sites of square and hexagonal structures simultaneously, with 400 atoms/trap and T=30 μK on average [2]. This is an easily scalable platform well suited for quantum information using Rydberg dipole blockade in atomic ensembles [2]. We present results of coherent Rabi oscillations between qubit states and initial experiments towards Rydberg mesoscopic ensembles.

References

[1] S. Whitlock, R. Gerritsma, T. Fernholz and R. J. C. Spreeuw, New J. Phys 11, 023021 (2009).
[2] V.Y.F Leung, D.R.M Pijn, H.Schlatter, L.Torralbo-Campo, A. La Rooij, G.B. Mulder, J.Naber, M.L. Soudijn, A. Tauschinsky, C. Abarbanel, B, Hadad, E. Golan, R. Folman, R.J.C. Spreeuw, Rev. of Sci. Int 88, 053102 (2014).
[3] A. Tauschinsky, R. M. T. Thijssen, S. Whitlock, H.B. van Linden van den Heuvell and R. J. C. Spreeuw, Phys.Rev. A 81, 063411 (2010).

Quantum Information Tu-077

Nanophotonic and CMOS-integrated architectures for trapped ion quantum information processing

Karan Mehta[1], Amira Eltony[1], Isaac Chuang[1], Rajeev Ram[1]

1. Research Laboratory of Electronics, Massachusetts Institute of Technology

We present an integrated optics architecture enabling scalable control and measurement for quantum information processing in planar ion traps. Single-mode waveguides distribute light to various locations in a dielectric layer in the same chip as the trap electrodes, and focusing grating couplers direct the light, through gaps in the trap electrodes, to micron-scale focuses at the ion locations. Recent advances in CMOS photonics suggest possible creation of such systems in foundry processes, which would allow practical integration of many couplers, avalanche photodiodes for readout, and electro-optic modulators, and control electronics together with the trap electrodes; additionally, the optics approach proposed would bring performance advantages, including tighter focuses and attendant advantages for individual addressing and laser power requirements, higher collection efficiencies, phase stability owing to reduced free-space path lengths, and pointing stability from inherent alignment. We present also experimental progress to these goals.

Experimental test of state-independent quantum contextuality of an indivisible quantum system

Yun-Feng Huang, Meng Li, Dong-Yang Cao, Chao Zhang, Yong-Sheng Zhang, Bi-Heng Liu,
Chuan-Feng Li, Guang-Can Guo

1. Key Laboratory of Quantum Infomation,Univesity of Scienticey of China,CAS

Since the quantum mechanics was born,quantum mechanics was argued among scientists because the differents between quantum mechanics and the classical physics. Because of this,some people give hidden variable theory. One of the hidden variable theory is non-contextual hidden variable theory, and KS inequalities are famous in non-contextual hidden variable theory.

But the original KS inequalities have 117 directions to measure, so it is almost impossiable to test the KS inequalities in experiment. However, about two years ago, Sixia Yu and C.H.Oh point out that for a single qutrit, we only need to measure 13 directions, then we can test the KS inequaties. This makes it possiable to test the KS inequalities in experiment.

We use the polarization and the path of single photon to construct a qutrit, and we use the half-wave plates, the beam displacers and polar beam splitters to prepare the quantum state and finish the measurement. And the result prove that quantum mechanics is right and non-contextual hidden variable theory is wrong.

Transfer and qubit fidelity of single atoms in a ring lattice

Mingsheng Zhan[1, 2], Shi Yu[1, 2, 3], Peng Xu[1, 2], Min Liu[1, 2], Xiaodong He[1, 2], Jin Wang[1, 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

Controllable transfer of atomic qubits opens a route to quantum information storage and processing. We demonstrate transferring of single atoms in a ring lattice with an auxiliary optical tweezers [1]. Single atoms follow the deeper tweezers and move to the determined position with high efficiency of 95% when they cross the static lattice. Comparison with other schemes [2, 3], it is more convenient for application, especially for single atoms array. Qubit fidelity is analyzed by quantum state tomography during the transportation. Additionally, the coherence properties of single atoms are investigated in detail via spin echo techniques. The reduced fidelity results from the instability of the movable tweezers and the heating of atoms. Dephasing in this process could be suppressed by stabilizing the laser intensity and by reducing the pointing fluctuations. Application of this scheme in quantum information processing is prospected.

References

[1] S. Yu, P. Xu, X. D. He, M. Liu, J. Wang, and M. S. Zhan, Opt. Express 21, 32130(2013).
[2] S. Kuhr, W. Alt, D. Schrader, et al., Phys. Rev. Lett. 91, 213002 (2003).
[3] J. Beugnon, C. Tuchendler, H. Marion, A. Gaëtan, Y. Miroshnychenko, Y. R. P. Sortais, A. M. Lance, M. P. A. Jones, G. Messin, A. Browaeys and P. Grangier, Nat. Phys. 3, 696 (2007).

Quantum Optics and Cavity QED Tu-080

Scalable Source of Multipartite Continuous Variable Entangled Beams of Light

Alberto Marino[1], Jietai Jing[2, 3], Zhongzhong Qin[2, 3], Leiming Cao[2, 3], Hailong Wang[2, 3], Weiping Zhang[2, 3]

1. *Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, Norman, Oklahoma 73019, USA*
2. *State Key Laboratory of Precision Spectroscopy, Department of Physics, East China Normal University, Shanghai 200062, China*
3. *Quantum Institute for Light and Atoms, Department of Physics, East China Normal University, Shanghai 200062, China*

The development of efficient and scalable sources of multipartite entanglement is required for the further development of quantum information. We propose a scalable configuration based on cascaded four-wave mixing (FWM) processes for the generation of multipartite CV entanglement. The FWM process is based on a double-lambda configuration in rubidium vapor and has been previously used to generate highly entangled twin beams. In the proposed configuration, one of the twin beams is used to seed another FWM process. We have experimentally verified that two cascaded FWM processes lead to the generation of three beams that contain quantum correlations in the form of intensity-difference squeezing and show that the level of squeezing produced by the first FWM process is increased by the second one. We derive a necessary criterion for the presence of multipartite entanglement that shows that one should expect the beams generated by the cascaded FWM processes to be entangled.

Quantum Optics and Cavity QED Tu-081

Photon-added nonlinear coherent states for a one mode field in a Kerr medium

José Récamier[1], Ricardo Román[1], Carlos González[1]

1. *Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, Apdo. Postal 48-3, Cuernavaca, Morelos 62251, México*

We construct deformed photon added nonlinear coherent states by application of a deformed creation operator upon the nonlinear coherent states obtained as eigenstates of the deformed annihilation operator and by application of a deformed displacement operator upon the vacuum state. We evaluate some statistical properties like the Mandel parameter, Husimi and Wigner functions for each of these states and analyze their differences [1]. We give closed analytical expressions for them.

References

[1] R. Román-Ancheyta, C. González-Gutiérrez, J. Récamier, J. Opt. Soc. Am. B 31, 38 (2014)

Advanced single photon sources with fiber-based optical microcavities

David Hunger[1, 2], Hanno Kaupp[1, 2], Helmut Fedder[3], Thomas Grange[4], Alexia Auffeves[4],
Christoph Becher[5], Theodor W. Hänsch[1, 2]

1. *Faculty of Physics, Ludwig-Maximilians-University, Schellingstr. 4, 80799 Munich, Germany*
2. *Max-Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*
3. *Physikalisches Institut, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart*
4. *CNRS and University of Grenoble, Institut Neel, F-38042, Grenoble, France*
5. *Universität des Saarlandes, Fachrichtung Experimentalphysik, Campus E2.6, 66123 Saarbrücken, Germany*

Fiber-based optical microcavities [1,2] combine small mode volume and large quality factors with full tunability and open access. We use enhanced light-matter coupling in the cavity to realize improved single photon sources with colour centers in diamond [3] in two complementary regimes: First, we demonstrate broadband Purcell enhancement of fluorescence from nitrogen-vacancy centers in diamond nanocrystals coupled to a low Q cavity with sub-λ^3 mode volume. Second, we discuss the generation of indistinguishable single photons under ambient conditions by coupling the emission from silicon-vacancy centers to high Q ($>10^6$) cavities. We report on first experimental steps in this direction.

References

[1] D. Hunger et al., New Journal of Physics 12, 065038 (2010)
[2] D. Hunger et al., AIP Advances 2, 012119 (2012)
[3] H. Kaupp et al., PRA 88 053812 (2013)

Quantum optics with hot Rydberg atoms

Alban Urvoy[1], Renate Daschner[1], Georg Epple[1], Bernhard Huber[1], Kathrin Kleinbach[1], Andreas Kölle[1], Harald Kübler[1], Fabian Ripka[1], Ralf Ritter[1], Robert Löw[1], Tilman Pfau[1]

1. 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart

The exceptionally strong interaction between highly excited Rydberg atoms enables applications in fields such as quantum optics, quantum computing, quantum simulation and metrology. If however they are to be used routinely in applications, a major requirement is their integration into technically feasible, miniaturized devices. Here we give an overview on our experiments on thermal Rydberg atoms confined in microscopic vapor cells or hollow core fibers [1]. We will present data on the coherent excitation to Rydberg states and how the Rydberg-Rydberg interaction alters the excitation dynamics [2]. We also report on the development of complex vapor cells e.g. including conductive structure for manipulating and detecting Rydberg atoms [3]. Finally, we will present our progress towards a room temperature single photon source.

References

[1] G. Epple et al., arXiv:1402.2195 (2014)
[2] T. Baluktsian et al., Phys. Rev. Lett. 110, 123001 (2013)
[3] R. Daschner et al., arXiv:1403.1093 (2014)

Cross-Modulation of Two Laser Beams at the Individual Photon Level

Kristin Beck[1], Wenlan Chen[1], Mahdi Hosseini[1], Qian Lin[1], Michael Guillans[2, 3], Mikhail Lukin[2], Vladan Vuletic[1]

1. Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
2. Department of Physics, Harvard University, Cambridge, MA 02138, USA
3. Joint Quantum Institute, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

Deterministic photon-photon interactions are a long-standing goal in optical science. Using an atomic ensemble inside a cavity, we demonstrate the mutual cross modulation of two continuous light beams at the level of individual photons. The originally uncorrelated beams derived from independent lasers become anticorrelated, as evidenced by an equal-time cross-correlation function $g^{(2)} = 0.89(1)$, showing that one photon in one beam extinguishes a photon in the other beam with a probability of 11(1)%. We also report recent progress using this approach for non-destructive continuous detection of traveling optical photons.

Single Photon Transistor in Circuit Quantum Electrodynamics

Lukas Neumeier[1, 2], Martin Leib[2], Michael Hartmann[2]

1. *ICFO-The Institute of Photonic Sciences*
2. *TUM- Technical University Munich*

Photons are the most suitable carrier for transmitting information over long distances as they are largely immune to environmental perturbations, and can propagate with very low loss and long-lived coherence in a wide range of media. The use of photons in information processing however still suffers from the inability to realize controlled, strong interactions between individual photons. For this reason we introduce a circuit quantum electrodynamical setup for a "single-photon" transistor. In our approach photons propagate in two open transmission lines that are coupled via two interacting transmon qubits. The interaction is such that no photons are exchanged between the two transmission lines but a single photon in one line can completely block respectively enable the propagation of photons in the other line. High on-off ratios can be achieved for feasible experimental parameters.

Characterization of Non-Classical Photonics States Retrieved from a Cold Atomic Memory and Quantum Statistics of Light Transmitted through Intracavity Rydberg medium.

Rajiv Boddeda[1], Erwan Bimbard[1], Nicolas Vitrant[1], Andrey Grankin[1], Imam Usmani[1], Valentina Parigi[2], Jovica Stanojevic[1], Etienne Brion[3], Alexei Ourjoumtsev[1], Philippe Grangier[1]

1. *Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ. Paris Sud, 2 avenue Augustin Fresnel, 91127 Palaiseau cedex, France*
2. *Laboratoire Kastler Brossel, Université Pierre et Marie Curie, École Normale Supérieure, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France.*
3. *Laboratoire Aimé Cotton, CNRS / Univ. Paris-Sud / ENS-Cachan, Bât. 505, Campus d'Orsay, 91405 Orsay, France*

Quantum states of light are one of the foremost and robust candidates for quantum information transportation and processing. Cold atomic ensembles are a prime choice to store and manipulate quantum states of light [1]. However, very often the light states stored or engineered in such systems are characterized only partially using photon counting statistics [2-4]. We demonstrate an on-demand retrieval of single photons by implementing the DLCZ protocol [5] in a cavity enhanced cold atomic memory . Single photon states were recovered with high efficiency (up to 82%) in a well defined spatio-temporal mode and consistently characterized by photon counting and homodyne tomography [6].

We theoretically investigate the quantum statistical properties of light transmitted through a cavity-enhanced atomic medium with strong optical nonlinearity induced by Rydberg-Rydberg van der Waals interactions [7]. Currently, an experiment is in progress to characterize the transmitted light by measuring the second order correlation function.

References

[1] A. I. Lvovsky, B. C. Sanders, and W. Tittel, Nat. Photonics 3, 706 (2009). [2] Y. O. Dudin and A. Kuzmich, Science 336 887 (2012). [3] T. Peyronel et al., Nature 488, 57 (2012). [4] D. Maxwell et al., Phys. Rev. Lett. 110, 103001 (2013). [5] L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature 414, 413 (2001). [6] E. Bimbard et al. Phys. Rev. Lett. 112 033601 (2014). [7] A. Grankin et al. New J. Phys. 16 043020 (2014).

Reversing the temporal envelope of an heralded single photon using a cavity

Bharath Srivathsan[1], Gurpreet Kaur Gulati[1], Alessandro Cerè[1], Brenda Chng[1], Christian Kurtsiefer[1, 2]

1. *Center for Quantum Technologies, 3 Science Drive 2, Singapore, 117543*
2. *National University of Singapore, 2 Science Drive 3, Singapore, 117542*

We demonstrate a way to prepare single photons with a temporal envelope that resembles the time reversal of photons from the spontaneous decay process. We use the photon pairs generated from a time-ordered atomic cascade decay as a starting point: the detection of the first photon of the cascade is used as a herald [1,2]. We show how coupling the heralding photon into an asymmetric Fabry-Perot cavity reverses the temporal shape of the heralded photon from a decaying to a rising exponential envelope. A single photon with such an exponentially rising temporal envelope would be ideal for interacting with two level systems. Using the analogy between an atom and a cavity [3] we demonstrate a proof-of-principle experiment on how these photons can be used for strong interaction with a single atom.

References

[1] B. Srivathsan et.al., Phys. Rev. Lett. 111, 123602 (2013).

[2] G. K. Gulati et.al., arXiv:1402.5800 (2014).

[3] M. Bader et.al., New Journal of Physics 15, 123008 (2013).

Quantum Optics and Cavity QED Tu-088

Phase-dependent double-Λ electromagnetically induced transparency

Yong-Fan Chen[1], Yi-Hsin Chen[2], Yi-Ting Liao[1], Ite A. Yu[2], Ying-Cheng Chen[3]

1. *Department of Physics, National Cheng Kung University, Tainan, 70101, Taiwan*
2. *Department of Physics, National Tsing Hua University, Hsinchu, 30013, Taiwan*
3. *Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 10617, Taiwan*

We theoretically investigate a phase-dependent double-Λ electromagnetically induced transparency (EIT) system. The property of the double-Λ EIT medium with a closed-loop configuration depends on the relative phase of the applied laser fields. This phase-dependent mechanism makes the double-Λ medium is different form the conventional Kerr-based nonlinear medium which only depends on the intensities of the applied laser fields. A steady-state analytical solution of the double-Λ EIT system is obtained by solving the Maxwell-Bloch equations. Additionally, we experimentally demonstrate an efficient all-optical π phase modulation based on the double-Λ EIT scheme in cold Rubidium atoms.

Observation of Spinor Slow Light

Meng-Jung Lee[1], Julius Ruseckas[2], Chin-Yuan Lee[1], Viaceslav Kudriasov[2], Kao-Fang Chang[1],
Hung-Wen Cho[1], Gediminas Juzeliunas[2], Ite A. Yu*[1]

1. *Department of Physics and Frontier Research Center on Fundamental and Applied Sciences of Matters, National Tsing Hua University, Hsinchu 30013, Taiwan*
2. *Institute of Theoretical Physics and Astronomy, Vilnius University, A. Gostauto 12, Vilnius 01108, Lithuania*

We report the first experimental demonstration of two-component or spinor slow light (SSL) using a double tripod (DT) atom-light coupling scheme [1]. Based on the interaction between the two slow light components, we observed the neutrino-type oscillations controlled by the two-photon detuning. In a proof-of-principle measurement, our data showed that the DT scheme for the light storage behaves like the two outcomes of a Mach-Zehnder interferometer enabling measurements of the frequency detuning. We also experimentally demonstrated a possible application of the DT scheme as quantum memory/rotator for the two-color qubit. Furthermore, the SSL may lead to interesting physics such as Dirac particles and spinor Bose-Einstein condensation of dark-state polaritons. It can also be used to achieve high conversion efficiencies in the sum frequency generation and is a far more superior method than the widely-used double-Λ scheme. This work opens up a new direction in the EIT/slow light research.

References

[1] M.-J. Lee, J. Ruseckas, C.-Y. Lee, V. Kudriasov, K.-F. Chang, H.-W. Cho, G. Juzeliunas, and I. A. Yu, arXiv:1404.6616 [quant-ph].

Three-photon electromagnetically induced absorption in a ladder-type atomic system

Han Seb Moon[1], Taek Jeong[2]

1. *Department of Physics, Pusan National University, 30 Jangjun-Dong, Geumjeong-Gu, Busan 609-735, Korea*

We report on three-photon electromagnetically induced absorption (TPEIA) due to three-photon coherence in ladder-type atomic systems for the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ transition in ^{87}Rb atoms. When a counterpropagating coupling field was added to the typical ladder-type electromagnetically induced transparency (EIT) experiment, both EIT and two-photon absorption (TPA) switched to TPEIA.Considering three-photon coherence in a Dopplerbroadened three-level ladder-type atomic system, the spectrum of the switch from EIT and TPA to TPEIA was numerically calculated and could be understood by decomposing the calculated spectrum into two-photon coherence and three-photon coherence components.

References

[1] H. S. Moon and T. Jeong. Phys. Rev. A 89, 033822 (2014).

Line Properties of the Ladder-type Electromagnetically Induced Transparency

Chin-Chun Tsai[1], Zong-Syun He[1], Jing-Yuan Su[1], Meng-Huang Sie[1], Jyun-Yan Ye[1], Nguyen Hien[1]

1. Department of Physics, National Cheng-Kung University, Tainan, Taiwan 70101

The relative intensities and line shape of the probe transmission in a ladder-type electromagnetically induced transparency (EIT) system by considering the optical pumping effect thoroughly are elucidated. The observed EIT spectra reveal a different probe or coupling power dependence for various transmission peaks. In addition to causing quantum interference, the probe, and coupling laser fields realign the population of Zeeman sublevels in the ground state through optical pumping. Analytical simulation results show a good agreement with the experimental observations.

Investigation of dynamical features in Λ-EIT atomic systems through noise correlation spectroscopy

Klara Theophilo[1], Hans Flores[1], Ashok Kumar[1], Marcelo Martinelli[1], Paulo Nussenzveig[1]

1. LMCAL - Physics Institute - University of São Paulo

We present a study of a cold Rubidium ^{87}Rb ensemble under eletromagnetic induced transparency (EIT). Using noise correlation spectroscopy, we investigate the asymmetric atomic response to an increasing or decreasing scanning in the detuning of a probe in the EIT process.

The Λ-EIT involves Zeeman sublevel coupled by two beams with orthogonal circular polarizations coupling the transition F=1 -> F'=1. A repump coupling the transition F=2 -> F'=2 is added to recycle the population.

Experimentally, we explored the angle between the probes and repump detuning, intensity and incidence direction. Additionally, spectra in time domain were studied.

Our theoretical approach[1] models the system simply as a Λ coupling in a 3 level atom. Although this model contains the basic features of EIT, it is not enough to explain atomic response observed. As we wish to fully understand the dynamics and obtain the characteristic time scales of relaxation processes, we present here a more sophisticated model.

References

[1] - D. Felinto, L. S. Cruz, R. A. de Oliveira, H. M. Florez, M. H. G. de Miranda, P. Nussenzveig, M. Martinelli, and J. W. R. Tabosa ,Optics Express, Vol. 21, Issue 2, 1512 (2013)

Electromagnetically induced photonic bandgap in cold ^{87}Rb atoms

Min Seok Kim[1], Seung Jin Kim[1], Seok Tae Gang[1], Jung Bog Kim[1]

1. Department of Physics Education, Korea National University of Education, Chung-Buk, 363-871, Korea Republic of

An Electromagnetically induced photonic bandgap is formed in cold ^{87}Rb atoms using configuration of Λ-type electromagnetically induced transparency in which the strong coupling beam is replaced by a standing-wave. When the probe light is propagating along the standing-wave, we are able to observe the transmission and the reflection behaviors of the weak probe beam. We studied the properties of electromagnetically induced photonic band gaps as the frequency detuning, polarization, or intensity of the coupling beam.

Synchronization in Superradiant Lasers

Kevin Cox[1], Joshua Weiner[1], Matthew Norcia[1], James Thompson[1]

1. JILA, NIST, and University of Colorado at Boulder

Superradiant lasers using cold atoms operate in a unique regime of laser physics where laser coherence is generated by spontaneous synchronization of the optical dipoles of an ensemble of atoms. Our rubidium superradiant laser offers unique access to this atomic synchronization process. We have recently studied superradiant synchronization in two experiments, observing for the first time both synchronization of a lasing superradiant ensemble to an external driving field and spontaneous synchronization of two superradiant ensembles. Here we present recent results from the two experiments with applications for the fundamental study of non-equilibrium phase transitions, synchronization of quantum oscillators, and possible generation of exotic many-body states in an open quantum system.

Imaging the Rydberg Electron Wavefunction

Tara Cubel Liebisch[1], Graham Lochead[1], Michael Schlagmüller[1], Huan Nguyen[1], Udo Hermann[1], Karl Magnus Westphal[1], Robert Löw[1], Tilman Pfau[1]

1. PI5 IQST, Universität Stuttgart, Pfaffenwaldring 57 D-70550 Stuttgart, Germany

An electron excited to a Rydberg state has an orbital radius larger than optical wavelengths and polarizes 1000s of ground state atoms in a dense medium such as a BEC. The interaction of the electron with the ground state atoms can be described by a pseudopotential linearly dependent on the ground state atom density. This interaction energy alters the density of the surrounding ground state atoms offering the possibility to image the probability density of the Rydberg electron imprinted in a dense medium [1]. We report on the progress of imaging the electron wavefunction of a single Rydberg atom in a ^{87}Rb BEC with 1µm resolution. The density modulation signal will increase due to multiple Rydberg excitations created using an excitation laser focused through the center of the BEC. First experiments concentrate on nS Rydberg states with n in the range of 100-160.

References

[1] T.Karpiuk et. al. arXiv:1402.6875

Dipolar transport in ultracold Rydberg gases

Georg Günter[1], Hanna Schempp[1], Martin Robert-de-Saint-Vincent[1], Vladislav Gavryusev[1],
Miguel Ferreira Cao[1], Stephan Helmrich[1], Christoph S. Hofmann[1], Shannon Whitlock[1],
Matthias Weidemüller[1]

1. Physikalisches Institut, Universität Heidelberg, Heidelberg Germany

Interfacing laser light with electronically highly excited (Rydberg) atoms allows to engineer synthetic systems for simulating coherent-quantum and open-system many-body dynamics. Rydberg atoms experience state changing interactions similar to Förster processes in complex molecules, offering a model system to study the nature of dipole-mediated energy transport in a controlled many-body system. We apply a new imaging technique to monitor the migration of Rydberg excitations with high time and spatial resolution [1,2]. The many-body dynamics is determined by continuous spatial projection of the electronic quantum state which establishes an environment for the transport dynamics [2]. With the available control of interactions and environment via the laser fields, we show that this system opens the way to studying the transition from classical to quantum transport as well as to investigations of dipolar transport phenomena which could ultimately shed new light on the nature of energy and spin transport in complex quantum systems.

References

[1] G. Günter et al, PRL 108, 013002 (2012).
[2] G. Günter et al, Science 342, 954 (2013).

Spin squeezing and supersolids using Rydberg-dressed strontium atoms

Daniel Sadler[1], Danielle Boddy[1], Alistair Bounds[1], Charles Adams[1], Elizabeth Bridge[1], Matthew Jones[1]

1. Joint Quantum Centre Durham-Newcastle (Durham University)

Coherent excitation of cold atoms to Rydberg states provides a new platform for quantum many-body physics. We demonstrate the utility of divalent atoms in this pursuit, showing that laser excitation of the second valence electron enables spatially resolved, state-selective detection of Rydberg atoms with single-atom sensitivity [1] and full access to counting statistics [2]. Strontium’s narrow intercombination lines not only provide the option to cool to the photon recoil limit but also enable two-photon excitation to the Rydberg state with low decoherence, providing an ideal system to investigate "Rydberg dressing". Here, a strong, off-resonant coupling to the Rydberg state introduces a new, tunable, soft-core interaction between the atoms, with potential for the formation of a Rydberg supersolid phase [3]. With the MPIPKS Dresden we show that applying this dressed interaction to strontium lattice clocks can also lead to the generation of significant spin squeezing that could be used to improve the signal-to-noise ratio [4]. We will present the first indications of Rydberg Blockade in a divalent atom in addition to the status of experiments seeking to observe Rydberg dressing.

References

[1] J. Millen et al., Phys. Rev. Lett. 105 213004 (2010)
[2] G.Lochead et al., Phys. Rev. A 87 053409 (2013)
[3] N. Henkel et al., Phys. Rev. Lett. 104 195302 (2010)
[4] L. Gil et al., Phys. Rev. Lett. 112, 103601 (2014)

Rydberg Atoms Tu-098

Ultralong Range Rydberg Molecules of Strontium

B. J. DeSalvo[1], J. A. Aman[1], F. B. Dunning[1], T. C. Killian[1]

1. Rice University

We report the formation of ultralong range Rydberg molecules in a thermal gas of neutral strontium. This work serves as an important first step in characterizing electron-ground state atom interactions in strontium. Using two photon excitation through the metastable $^3P_1$ state, we create molecules in the $5sns^3S_1$ Rydberg series in the vicinity of n = 35. Molecule formation is detected as a loss of atoms from an optical dipole trap. Understanding these molecules lays the foundation for our future work in Rydberg excitation and Rydberg dressing of a Bose Einstein condensate of strontium. I will also describe progress towards these ends.

Ultrafast coherent control of an ultracold Rydberg gas

Nobuyuki Takei[1, 2, 3], Christian Sommer[1, 2, 3], Haruka Goto[1], Kuniaki Koyasu[1, 2, 3], Hisashi Chiba [1, 3, 4], Guido Pupillo[3, 5], Claudiu Genes[3, 6], Matthias Weidemüller[3, 7], Kenji Ohmori[1, 2, 3]

1. *Institute for Molecular Science, National Institutes of Natural Sciences, Myodaiji, Okazaki 444-8585, Japan*
2. *SOKENDAI (The Graduate University for Advanced Studies), Okazaki 444-8585, Japan*
3. *CREST, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan*
4. *Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka, Iwate 020-8551, Japan*
5. *IPCMS (UMR 7504) and ISIS (UMR 7006), University of Strasbourg and CNRS, 67000 Strasbourg, France*
6. *Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria*
7. *Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany*

We investigate many-body interactions in an ensemble of ultracold Rydberg atoms by means of ultrafast coherent control with attosecond precision [1]. A picosecond laser pulse produces Rydberg electronic wave-packets in a cloud of laser-cooled Rb atoms prepared in an optical dipole trap. The bandwidth of our picosecond laser pulse is larger than that of the CW or nanosecond-pulsed laser employed in previous experiments with ultracold Rydberg atoms [2,3], so that our Rydberg-blockade radius is significantly smaller. This allows for a high density of Rydberg atoms and consequently for strong many-body interactions, which modulate the temporal evolution of the wave-packets. The strength of the interactions is actively tuned by changing the atom density and the principal quantum number. In this presentation, we will discuss the atom-density dependence of the Rydberg wave-packet interferogram. This technique could be a novel approach to investigating quantum many-body dynamics.

References

[1] K. Ohmori, Found. Phys. DOI 10.1007/s10701-014-9773-5.
[2] M. Saffman, T. Walker, and K. Mølmer, Rev. Mod. Phys. 82, 2313-2363 (2010).
[3] R. Löw et al., J. Phys. B: At. Mol. Opt. Phys. 45, 113001 (2012).

Rydberg Atoms Tu-100

Dynamical crystallization in a low-dimensional Rydberg gas

Sebastian Hild[1], Peter Schauß[1], Johannes Zeiher[1], Takeshi Fukuhara[1], Marc Cheneau[2], Tommaso Macri[3], Thomas Pohl[3], Immanuel Bloch[1, 4], Christian Groß[1]

1. Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
2. Laboratoire Charles Fabry - Institut d'Optique, Palaiseau, France
3. Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Straße 38, 01187 Dresden, Germany
4. Fakultät für Physik, Ludwig- Maximilians-Universität München, Schellingstraße 4, 80799 Münnchen, Germany

Rydberg gases offer the possibility to study long-range correlated many-body states due to their strong van der Waals interactions. In our setup, we optically excite Rydberg atoms and detect them with submicron resolution, which allows us to measure spatial correlations of resulting ordered states. Starting from a two dimensional array of ground state atoms in an optical lattice, we couple to a Rydberg state in a two-photon excitation scheme. Using numerically optimized pulse shapes for coupling strength and detuning, we deterministically prepare the crystalline state in this long-range interacting many-body system. Control of the spatial configuration of the initial state is of great importance for the investigation of the phase diagram. To achieve this, we developed an experimental scheme based on single site addressing allowing for preparation of initial states with sub-Poisson number fluctuations.

Rydberg Atoms Tu-101

Rydberg blockade in an optical lattice

E. A. Goldschmidt, D. G. Norris, R. C. Brown, S. Koller, R. Wyllie, A. Hu, A. V. Gorshkov, M. S. Safronova, S. L. Rolston, J. V. Porto

1. Joint Quantum Institute, NIST and the University of Maryland, Room 2207 Computer and Space Sciences Building, College Park, MD 20742

Ultracold Rydberg atoms are a promising system to study quantum many body effects due to their strong Rydberg interactions. The strength of the interaction is tunable via the principal quantum number of the Rydberg state, and we choose a regime where only nearest neighbors in our optical lattice are strongly blockaded. We perform fluorescence spectroscopy of the 18S Rydberg level in ultracold Rb-87 by exciting a two-photon transition with intermediate detuning near the D1 line and detecting photons emitted on the D2 line with a single photon avalanche diode. We use this technique to measure a magic wavelength, where there is no differential light shift between the ground and Rydberg state, near 1064 nm to better than 1 GHz. We also report initial progress toward spectroscopy in a 3D optical lattice in which the Rydberg blockade effect should allow us to generate collective states that exhibit large spatial and temporal correlations.

Tune-out wavelengths for metastable helium

Kenneth Baldwin[1], Bryce Henson[1], Robert Dall[1], Andrew Truscott[1], James Mitroy[2], Li-Yan Tang[3]

1. Research School of Physics and Engineering, Australian National University, Canberra, A.C.T. 0200 Australia
2. School of Engineering and Information Technology, Charles Darwin University, Darwin, NT 0909, Australia
3. State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, People's Republic of China

Tune-out wavelengths occur near atomic transitions where the opposite sign of the respective contributions to the dynamic polarizability of the atom cancel to yield a net zero polarizability [1]. Mitroy et al. [2] have estimated the locations of the tune-out wavelengths associated with the metastable helium at the 0.1% level in order to provide a guide to experimental investigations. If the tune-out wavelength can be determined to an absolute accuracy of 100fm (~0.2 ppm), then the fractional uncertainty in the derived structure information would be 1.8 ppm [2]. We will employ our metastable helium facility used in previous precision measurements [3] to determine the effect of a light field near the 413nm tune-out wavelength on the trap frequency, and later employ our new atom interferometer facility to accurately measure the tune-out wavelength of light illuminating the metastable helium atoms for which there is no change in the interferometric fringe position.

References

1. "Species-specific optical lattices", L. J. LeBlanc and J. H. Thywissen, Phys. Rev. A 75, 053612 (2007).
2. "Tune-out wavelengths for metastable helium", J. Mitroy and Li-Yan Tang, Phys. Rev. A 88, 052515 (2013).
3. "Metastable helium: A new determination of the longest atomic excited-state lifetime", S.S. Hodgman, R.G. Dall, L.J. Byron, K.G.H. Baldwin, S.J. Buckman and A.G. Truscott, Phys. Rev. Lett. 103, 053002, (2009).

Magic polarization to eliminate Stark-induced dephasing in an optical trap

Huidong Kim[1], Hyok Sang Han[1], D. Cho[1]

1. *Department of Physics, Korea University, Seoul, Korea*

We demonstrate that the differential ac-Stark shift of a ground hyperfine transition in an optical trap can be eliminated by using properly polarized trapping light. We use the polarization dependence of the Stark shift via vector polarizability that resembles a Zeeman shift. We study a Zeeman-sensitive transition from the $|2S_{1/2}, F = 2, m_F = -2\rangle$ to the $|2S_{1/2}, F = 1, m_F = -1\rangle$ state of ^{7}Li. By using magic polarization we observed 0.59 ± 0.02 Hz linewidth for Rabi transition with interrogation time 2 s and 0.82 ± 0.06 s coherence time for a superposition state. These are improvements over previous results by at least two orders of magnitude. We hope that the magic polarization brings breakthroughs in precision spectroscopy and quantum information processing just as the magic wavelength did in frequency metrology and cavity quatum electrodynamics.

Magic Frequencies in Atom-Light Interaction for Precision Probing of the Density Matrix

Yair Margalit[1], Menachem Givon[1], Amir Waxman[1], Tal David[2], David Groswasser[1], Yonathan Japha[1], Ron Folman[1]

1. *Ben-Gurion University of the Negev, P.O. Box 653, Beer Sheva 84105, Israel*
2. *Israel Aerospace Industries, Ramta Division, 1 Nafha Street, Beer Sheva 84102, Israel*

We analyze theoretically and experimentally [1] the existence of a magic frequency for which the absorption of a linearly polarized light beam by a vapor of alkali-metal atoms is independent of the population distribution among the Zeeman sublevels and the angle between the beam and an external magnetic field, which defines the quantization axis. From a fundamental point of view, the magic frequency represents a unique cancellation of the contributions of higher moments of the atomic density matrix to light absorption, so that light-matter interaction becomes rotationally invariant although the atomic sample as well as the light beam and its polarization all have a well-defined direction. The phenomenon is described using the Wigner-Eckart theorem and inherent properties of Clebsch-Gordan coefficients. One important application is the robust measurement of the hyperfine population. We experimentally demonstrate the magic frequency on an ensemble of rubidium atoms inside a vapor cell.

References

[1] M. Givon, Y. Margalit, A. Waxman, T. David, D. Groswasser, Y. Japha, and R. Folman, Phys. Rev. Lett. 111, 053004 (2013).

Tailoring light to enhance forbidden atomic transitions rates

Rocio Jauregui

1. *Instituto de Fisica, Universidad Nacional Autonoma de Mexico*

The coupling between the electric dipole moment **d** of an atom to the electric field **E** of an electromagnetic wave, **d .E**, yields optical dipole transition amplitudes, so that the corresponding transition rates |**d .E**|^2 are proportional to the intensity of the pump field. Quadrupole and magnetic dipole atomic moments couple to the derivatives of **E**. We make a comparative study of different vectorial modes of the electromagnetic field that, having greater values of the derivatives of **E** with respect to standard paraxial Gaussian pump beams, enhance the quadrupole and magnetic dipole transition rates. We take polarization, focusing and topological structure (optical vortices and phase dislocations) as the relevant properties of the pump beams. The feasibility of the realization of optimal pump beams and the expected results for specific atomic transitions is also discussed.

Spectroscopy, Atomic and Molecular Structure Tu-106

Time-resolved measurement of velocity-changing collisions in a paraffin-coated alkali vapor cell

Naota Sekiguchi, Atsushi hatakeyama

1. *Tokyo University of Agriculture and Technology*

A paraffin coating on the walls of an alkali vapor cell might increase a residual gas pressure. In order to find out whether paraffin-coated cells contain a non-negligible buffer gas, we measure the effect of velocity-changing collisions (VCCs) on the microsecond time scale. The polarization of atoms that move perpendicular to laser beams is produced and measured by means of velocity-selective optical pumping. In addition to collisions with coated walls, VCCs with a buffer gas occur and affect the signals of the polarization if the cell contains a buffer gas. We can distinguish these collisions by time-resolved measurement because VCCs occur before wall collisions. Comparing the measurements for coated cells with that for non-coated cells, we can determine whether the coated cells contain a buffer gas.

Atom-surface interactions using a quadrupole oscillator strength sum rule

James Babb

1. ITAMP, Harvard-Smithsonian Center for Astrophysics

Characterizations of the long-range potentials for interactions between atoms or molecules and surfaces are of key interest for collisional and trapping studies. Knowledge of the electric dipole oscillator strength distribution of the atom or molecule provides one route to obtaining the interaction coefficient. In this paper an electric quadrupole oscillator strength sum rule is related to the atom-surface interaction. The utility of the approach for calculating interactions between various atoms and molecules and different surfaces is explored.

Adsorbate Electric Fields on a Cryogenic Atom Chip

Christoph Hufnagel[1, 2], Kin Sung Chan[1, 2], Mirco Siercke[1, 2], Rainer Dumke[1, 2]

1. Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore
2. Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore

We investigate the behaviour of electric fields originating from adsorbates deposited on a cryogenic atom chip as it is cooled from room temperature to cryogenic temperature. Using Rydberg electromagnetically induced transparency we measure the field strength versus distance from a 1mm square of YBCO patterned onto a YSZ chip substrate. We find a localized and stable dipole field at room temperature and attribute it to a saturated layer of chemically adsorbed rubidium atoms on the YBCO. As the chip is cooled towards 83K we observe a change in sign of the electric field as well as a transition from a localized to a delocalized dipole density. We relate these changes to the onset of physisorption on the chip surface when the van der Waals attraction overcomes the thermal desorption mechanisms [1] .

References

[1] K.S. Chan, M. Siercke, C. Hufnagel and R. Dumke, PRL 112, 026101 (2013).

Relaxation of Cs atomic polarization at surface coatings characterized by x-ray photoelectron spectroscopy

Kotaro Kushida[1], Takemasa Moriya[1], Toshihiro Niwano[1], Tomohito Shimizu[1], Hideki Nakazawa[2], Atsushi Hatakeyama[1]

1. Tokyo University of Agriculture and Technology
2. Hirosaki University

We study anti-relaxation surface coatings in order to preserve atomic spin polarization in alkali vapor cells. The polarization of the alkali atoms relaxes due to the collisions with the cell wall. However anti-relaxation surface coatings reduce the effects of spin relaxation at the wall of the cell. The most effective known anti-relaxation coating is paraffin, with which polarized alkali atoms may collide up to 10000 times before depolarizing. Its effectiveness varies considerably depending on the preparation skill of the individual involved. Relationship between the effectiveness and surface conditions had not been extensively studied. We made paraffin and diamond-like carbon (DLC) coated substrates by vacuum vapor deposition, and measured relaxation times for Cs vapor. We confirmed the anti-relaxation effect only with paraffin. According to x-ray photoelectron spectroscopy, effective anti-relaxation substrates had high carbon coverage.

Raman spectroscopy and NMR investigation of hydrocarbon anti-relaxation coatings upon interaction with an alkali-metal vapor

Oleg Yu. Tretiak[1], Pavel K. Olshin[2], Sergey N. Smirnov[3], John W. Blanchard[4, 5], Dmitry Budker[67, 8], Amber M. Hibberd[9], Mikhail V. Balabas[1]

1. *Department of Physics, Saint-Petersburg State University, Russian Federation*
2. *Resource Center "Optical and laser methods of material research", Saint-Petersburg State University, Russian Federation*
3. *Center for Magnetic Resonance, Saint-Petersburg State University, Russian Federation*
4. *Department of Chemistry, University of California at Berkeley, CA, 94720, USA*
5. *Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA*
6. *Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*
7. *Department of Physics, University of California at Berkeley, CA, 94720-7300, USA*
8. *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA*
9. *Intel corporation, Hillsboro, Oregon, 97124, USA*

New alkene-based anti-relaxation coating of alkali metal vapor cell demonstrated up to 10 times longer relaxation time then the same time for classical alkane-based coating [1]. The results of experimental investigations of the influence of alkali-metal vapor on different types of coating materials, via Raman spectroscopy and Nuclear Magnetic Resonance (NMR) Spectroscopy are presented. Standard coated alkali- metal vapor cells, coated glass wafers, and the same material inside special vacuum tubes were used as experimental samples. Alkene-based anti-relaxation - coating material from [1] was studied with the NMR method. Isomerization of alkene - double bond moving from the "alpha" position towards the center of the molecule was found. This work considerably extends the earlier studies of the anti-relaxation coatings by a variety of surface-science techniques [2].

References

[1] M. V. Balabas, T. Karaulanov, M. P. Ledbetter and D. Budker, Phys. Rev. Lett. 105, 070801 (2010)

[2] S. J. Seltzer, D. J. Michalak, M. H. Donaldson, M. V. Balabas, S. K. Barber, S. L. Bernasek, M.A. Bouchiat, A. Hexemer, A. M. Hibberd, D. F. Jackson Kimball, C. Jaye, T. Karaulanov, F. A. Narducci, S. A. Rangwala, H. G. Robinson, A. K. Shmakov, D. L. Voronov, V. V. Yashchuk, A. Pines, and D. Budker, Journ. Chem. Phys. 133, 144703 (2010)

Nonlinear spectroscopy of atoms inside a porous sample

Santiago Villalba[1]

1. Instituto de Fisica, Facultad de Ingenieria, Universidad de la Republica, J. Herrera y Reissig 565, 11300 Montevideo, Uruguay

The nonlinear response of Rb vapor inside the pores of a ground glass sample made of grains of a few tenth of micrometers was studied and shown to be affected by confinement and the spatial randomness of the light scattered by the sample. Sub-Doppler resonances were observed in Hanle spectroscopy and in a saturation-absorption-like pump-probe experiment arising from atoms near the sample surface. Specificities in the spectrum reveal the atomic confinement [1]. The spectroscopic examination of scattered light that has traversed the bulk of the sample does not show narrow Sub-Doppler resonances. This negative result is interpreted as a consequence of the speckle nature of the light inside the sample. Nonetheless, broad pump-probe spectral features are observed as a consequence of hyperfine optical pumping. The observed spectra are in good agreement with a simple model for two-photon interaction of atoms with thermal velocity distribution with random light.

References

[1] S. Villalba, A. Laliotis, L. Lenci, D. Bloch, A. Lezama and H. Failache. Phys. Rev. A, 89, 023422 (2014)

Cell influence on the absolute frequency of cesium atom 6S-8S hyperfine transition

Chien-Ming Wu, Tze-Wei Liu, *Wang-Yau Cheng

1. National Central University Jongli, Taoyuan 32001, Taiwan

Glass cells, like iodine cell, rubidium cell and so on, have been used for secondary standard for several of ten years. It is long believed that some unclear effects obstruct the atomic frequency measurements from cells since 10 kHz discrepancy between secondary standards were easy to be found. Here we report on one significant fact. We examined 10 cells for obtaining the absolute frequency of cesium atom 6S-8S hyperfine transition and, to our surprise, the frequency measurement results scattered over 400 kHz! We found that the frequency deviation determined from each cell has correlation with its linewidth [1]. To precisely measure the aforementioned linewidth, we develop a novel approach of stabilizing laser frequency by two-photon interfered spectrum that leads to higher resolution than previous result [2].

References

[1] Chien-Ming Wu, Tze-Wei Liu, Ming-Hsuan Wu, Ray-Kung Lee and Wang-Yau Cheng, "The absolute frequency of cesium 6S-8S 822-nm two-photon transition by a high-resolution scheme", Opt. Lett. 38, 3186 (2013). (Spotlight on Optics, OSA, 2013, September)

[2] P. Fendel, S. D. Bergeson, Th. Udem and T. W. Hansch, "Two-photon frequency comb spectroscopy of the 6s-8s transition in cesium" Opt. Lett. 32, 701 (2007)

Revised and extended analysis of trebly ionized selenium: Se IV

Hala Noman[1]

1. *Department of Physics, A.M.U., Aligarh*

The fourth spectrum of selenium has been investigated in the wavelength region 300-2080Å using triggered spark source. The ground configuration of Se IV is $4s^24p$ and its outer excitation is basically one-electron system with doublet structure while inner excitation leads to a three-electron system making structure more complex. We have studied the $4s^2np(n=4\text{-}7)+4s^2nf(n=4\text{-}6)+4p^3+4s4p(5s+6s+4d+5d)$ configurations in the odd parity system and $4s^2ns(n=5\text{-}7)+4s^25g$ configurations in the even parity matrix. In one electron spectrum, the levels of $4s^2$ (5s,6s,4p,5p,6p,4d,5d,4f and 5g) configurations are being confirmed but revised the levels of $4s^2$ (7s,7p,6d and 5f) configurations. In three-electron system, $4s4p^2\ {}^4S_{3/2}$ and all levels of $4p^3$ configuration have been revised. The 4s4p(4d+5d+5s+6s) configurations have been studied for the first time. Forty-six odd and seventeen even parity energy levels are now known based on the identification of three-hundred transitions. The Ionization limit was found to be 346721±265cm^{-1}(42.988±0.033eV). The analysis is supported by Hartree-Fock calculations. Parametric values of energy levels agreed well with the experimental values.

References

[1] M. S. Gautam and Y. N. Joshi, Can. J. Phys. 50, 2059–2062 (1972)

The fourth spectrum of tin: Sn IV

Haris Kunari[1], Tauheed Ahmad[1]

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

The spectrum of trebly ionized tin (Sn IV) has been investigated with the help of spectral recordings made on a 3m normal incidence vacuum spectrograph of Antigonish laboratory in Canada using a triggered spark light source. The ground configuration of Ag-like tin is $4d^{10}5s$. The outer electronic excitation gives rise to $4d^{10}n$▯ configurations with doublet structure, while inner electron excitation leads to form the configurations like $4d^95s$ [5p+4f], $4d^95s^2$ and $4d^95p^2$. We have confirmed all the reported levels [1, 2] belonging to one electron part but could not confirm all the levels of doubly excited configurations. The $4d^95s5p$- $4d^95p^2$ transitions lie around 1000-1500Å was turn out to be very helpful to confirm the reported levels of $4d^95p^2$ as well as to establish the new levels of $4d^95s5p$ with $J \geq 5/2$. The Hartree-Fock calculations by Cowan's code support the analysis.

References

[1] A Kramida, Yu Ralchenko, J. Reader; NIST ASD team, version 5, online, Gaithersburg, Maryland, USA, NIST, 2012, available from : (http://physics.nist.gov/asd). [2] A. N. Ryabtsev, S. S. Churilov, and É. Ya. Kononov, Optics and Spectroscopy, 100, pp. 652–659 (2006) and references therein. [3] A. N. Ryabstev, S. S. Churilov, and E. Ya. Kononov, Opt and Spectrosc 102, 354-362 (2007).

A New Simple Atom for Atomic Physics: e^+ bound to H^- in atomic state, H^{-+}

Cody Storry[1], Ivan Guevara[1], Matthew George[1], Eric Hessels[1], Richard Thai[1], Matthew Weel[1]

1. Department of Physics, York University

An H^- ion beam is directed through a sample of trapped e^+ from a radioactive source, producing long lived H^{-+} atoms. For production, ions are decelerated to ~50eV by an electric field from applied potentials on cylindrical electrodes. These electrodes along with an axial magnetic field produce a Penning trap for ~$10^7 e^+$ slowed and captured in this Surko-style e^+ accumulator. H^{-+} travel 2 meters and into a metal plate where back-to-back e+ annihilation gammas emitted are detected in coincidence. Typically systems with antimatter bound to matter have short lifetimes (and hence wide transition widths) due to annihilation. Rydberg states of H^{-+} have long radiative lifetimes and hence narrow transitions. The 2 meter transit indicates a survival time of ~5microseconds

We will also present research toward measurements of Rydberg positronium atomic structure.

Solitons, Interactionless BECs and Simultaneous Dual Isotopes in Atom Interferometry

Gordon McDonald[1], Carlos Kuhn[1], Kyle Hardman[1], Shayne Bennetts[1], Patrick Everitt[1], Paul Altin[1], John Debs[1], John Close[1], Nicholas Robins[1]

1. *Quantum Sensors Lab, Department of Quantum Science, Research School of Physics and Engineering, Australian National University, Canberra, 0200, Australia*

We demonstrate the first realisation of a solitonic atom interferometer, using a tunable-interaction condensate of Rubidium-85 in a horizontal optical waveguide [1]. By balancing the inherent matter-wave dispersion with a small attractive inter-atomic interaction, a non-dispersive cloud - a bright soliton - can be formed. We construct a Mach-Zehnder interferometer using this variable-interaction-strength condensate . It is found that the soliton interaction strength maximises the coherence time of the interferometer, over all other possible interaction strengths including an interactionless condensate.

Due to the sympathetic cooling process we employ to generate condensates of Rubidium-85, we can also produce dual condensates of both Rubidium-85 and Rubidium-87 in the same trap [2]. By loading both of these into the optical waveguide we can construct a simultaneous Mach-Zehnder interferometer on both isotopes. Such a scheme is proposed for Weak Equivalence Principle measurements. This allows cancellation of common-mode vibration noise sources. Also, we measure the phase shift on an interactionless Rubidium-85 Mach-Zehnder interferometer due to a variable number of coincident Rubidium-87 atoms, which should allow a precision measurement of the inter-isotope scattering length.

References

[1] Gordon D. McDonald, Carlos C. N. Kuhn, Kyle S. Hardman, Shayne Bennetts, Patrick J. Everitt, Paul A. Altin, John E. Debs, John D. Close, Nicholas P. Robins. arXiv:1403.3485 A Bright Solitonic Matter-Wave Interferometer. (2014)

[2] C.C.N. Kuhn, G.D. McDonald, K.S. Hardman, S. Bennetts, P.J. Everitt, P.A. Altin, J.E. Debs, J.D. Close, N.P. Robins. arXiv:1401.5827 A Bose-condensed, simultaneous dual species Mach-Zehnder atom interferometer. (2014)

Compact atom interferometer inertial sensor with radially expanding atom ensemble

Stefan Riedl[1], Greg Hoth[1], Elizabeth Donley[1], John Kitching[1]

1. NIST, 325 Broadway, 80305 Boulder, USA

We present our work toward a novel compact atom interferometer inertial sensor based on a single radially expanding ensemble of laser-cooled atoms interrogated by pulsed stimulated Raman transitions. The sensor design emphasizes small size and simplicity of operation, while potentially achieving a performance level suitable for inertial navigation. The expansion of the atom ensemble together with spatially-resolved detection enables the separation of acceleration-induced phase shifts from rotation-induced phase shifts, allowing acceleration and rotation to be independently measured. In addition, the ability to spatially resolve phase shifts across the cloud enables us to mitigate the effect of imperfections like magnetic field gradients, residual light shifts, and imperfections in the interrogation beams.

Atom Interferometry Tu-118

Agile narrow linewidth single source laser system for onboard atom interferometry

Fabien Theron[1], Yannick Bidel[1], Nassim Zahzam[1], Alexandre Bresson[1]

1. ONERA - The French Aerospace Lab, BP 80100, 91127 Palaiseau Cedex, France

Atom interferometers have demonstrated excellent performance for precision acceleration and rotation measurements [1]. Many researches have been made the last few years to develop transportable laser systems [2] and particularly to make the laser setup as compact and immune to perturbations as possible [3].

We realized a compact and robust laser system for rubidium atom interferometry based on a frequency-doubled telecom laser. Our frequency stabilization architecture allows us to tune dynamically the laser frequency over 1 GHz in few ms using only one laser source. Each laser frequency used for atom interferometry is created by changing dynamically the frequency of the laser or by creating sidebands using a phase modulator. We take advantage of the maturity of fiber telecom technology to make the setup compact, immune to vibrations and thermal fluctuations. The source provides spectral linewidth below 10 kHz required for precision atom interferometry, and particularly for atom gravity gradiometer.

References

[1] B. Canuel, F. Leduc, D. Holleville, A. Gauguet, J. Fils, A. Virdis, A. Clairon, N. Dimarcq, C. J. Bordé, A. Landragin, and P. Bouyer, Phys. Rev. Lett. 97, 10402 (2006).

[2] M. Schmidt, M. Prevedelli, A. Giorgini, G.M. Tino, and A. Peters, Appl. Phys. B 102, 11-18 (2011).

[3] R. Geiger, V. Ménoret, G. Stern, N. Zahzam, P. Cheinet, B. Battelier, A. Villing, F. Moron, M. Lours, Y. Bidel, A.Bresson, A. Landragin, and P. Bouyer, Nat. Commun. 2, 474 (2011).

A Mobile, Dual-Species Atom Interferometer for Equivalence Principle Tests in Micro-Gravity

Brynle Barrett[1], Laura Antoni-Micollier[1], Pierre-Alain Gominet[1], Baptiste Battelier[1], Arnaud Landragin[2], Philippe Bouyer[1]

1. *LP2N, CNRS, CNES, Université de Bordeaux, Institut d'Optique d'Aquitaine, rue Francois Mitterrand, 33400 Talence, France*
2. *LNE-SYRTE, CNRS, UPMC, Observatoire de Paris, 61 avenue de l'Observatoire, F-75014 Paris, France*

The ICE experiment is a compact and transportable atom interferometer designed to make precise tests of the weak equivalence principle (WEP) using two atomic species: ^{39}K and ^{87}Rb. The WEP states that two massive bodies will undergo the same gravitational acceleration regardless of their mass or composition. An atom-interferometric test of the WEP involves precisely measuring the relative acceleration of two different atoms. Since potassium and rubidium differ greatly in mass, but have similar internal structure, they are ideal choices for this type of test. Recently, we demonstrated the first airborne matter-wave interferometer, which operated in the micro-gravity environment created during the parabolic flights of the Novespace Zero-g aircraft [1]. The 20 seconds of $0g$ produced during each parabola allows us to extend the interrogation time and therefore the sensitivity of our interferometer. Here, we present our recent experimental results, including some of the first interferometric measurements with ^{39}K [2].

References

[1] R. Geiger, V. Ménoret, G. Stern, N. Zahzam, P. Cheinet, B. Battelier, A. Villing, F. Moron, M. Lours, Y. Bidel, A. Bresson, A. Landragin and P. Bouyer, Nature comm., 2, 472 (2011).

[2] B. Barrett, P.-A. Gominet, E. Cantin, L. Antoni-Micollier, A. Bertoldi, B. Battelier, P. Bouyer, J. Lautier, and A. Landragin, to be published in Proceedings of the International School of Physics "Enrico Fermi" on Atom Interferometry (2014).

Matter-wave laser Interferometer Gravitation Antenna (MIGA) experiment for fundamental physics and geoscience

Andrea Bertoldi, Benjamin Canuel, Jonathan Gillot, Isabelle Riou, Sebastian Schmid, Philippe Bouyer

1. LP2N, Laboratoire de Photonique Numérique et Nanosciences, Institut d'Optique Graduate School IOA, Rue François Mitterrand, 33400, Talence, FRANCE

The MIGA experiment will implement a hybrid sensor coupling laser and matter-wave interferometry to study sub-Hertz variations of the strain tensor of space-time and gravitation. An array of atomic interferometers will be simultaneously manipulated by the resonant optical field of a 200 m cavity. The system will use as gravity sensors both the suspended cavity mirrors, whose relative motion is optically monitored, and free falling atomic ensembles, probed with matterwave interferometry techniques. The experiment will be located underground at the LSBB laboratory in Rustrel (France), far from major anthropogenic disturbances and in an environment with a very low background noise [1]. The presence on site of several instruments to monitor the geophysical site (inclinometers, accelerometers, magnetometers, seismometers…) will be exploited to push the experimental sensitivity. We will report on the status of the small scale prototype that we will use to study cavity aided atom interferometry.

References

[1] T. Farah, et al. arXiv:1404.6722

Ytterbium Bose-Einstein condensate interferometer: current results and new construction.

Benjamin Plotkin-Swing, Alan Jamison, Subhadeep Gupta

1. University of Washington

We present the first ytterbium matter-wave interferometer using a Bose-Einstein condensate (BEC) source in a contrast interferometer geometry. We measure h/m, where h is Planck's constant and m is the mass of an ytterbium atom, in order to determine the fine structure constant α. We demonstrate theoretical understanding and experimental control over our two main sources of systematic error: atomic interactions and diffraction phases. Based on our findings, we present our plans for increasing the precision of our α measurement to the level of one part in ten billion. We also observed that the interferometer signal is sensitive to the condensate critical temperature, and we propose BEC interferometry as a tool for studying phase transitions. We will describe some of the features of a new apparatus for our next generation of measurements that is currently under construction.

Dynamic algebraically precise atom chip potentials

Eric A. Imhof[1], James A. Stickney[2], Brian Kasch[3], Christopher J. Erickson[3], John H. Burke[3],
Matthew B. Squires[3]

1. Air Force Institute of Technology
2. Space Dynamics Laboratory
3. Air Force Research Laboratory

Precision potentials for cold atom experiments are often limited by the placement of individual conductors and the resulting magnetic field shape. Traps and guides are typically created to achieve a singular purpose, with new experiments requiring redesigned coils or atom chips. We present a method to create customized, dynamic, and algebraically precise potentials over large distances along the axis of a cold atom waveguide near the surface of an atom chip. Our experimental results include demonstrations of a pure harmonic trap and a dynamic double well. We will present our methods for fabricating atom chips and the corresponding experimental setup.

Quantum interference experiments with macromolecules

Sandra Eibenberger[1], Xiaxi Cheng[1], Lukas Mairhofer[1], Joseph Cotter[1], Markus Arndt[1]

1. University of Vienna, Faculty of Physics, VCQ, QuNaBioS, Austria

The quest for testing the quantum superposition principle in the regime of high mass and complexity has motivated quantum interference experiments with macromolecules.

We present experiments in a Kapitza-Dirac-Talbot-Lau matter-wave interferometer [1,2] and report on the current mass record in de Broglie interference [3].

The sensitivity of molecular coherence to tiny external forces enables the investigation of internal molecular properties through measurements of dephasing and shifts of the molecular interference patterns. This has been exploited for the study of electric polarizability and moments in molecule interferometry in the presence of inhomogeneous electric fields [4,5].

Recently, we were able to demonstrate how to derive absolute photo-absorption cross sections from quantum interferometry [6]. The recoil imparted on each molecule upon absorption of a single photon leads to an effective reduction in quantum fringe visibility. This allows us to extract the cross section with high accuracy and independent of the molecular beam density.

References

[1] S. Gerlich, L. Hackermüller, K. Hornberger, A. Stibor, H. Ulbricht, M. Gring, F. Goldfarb, T. Savas, M. Müri, M. Mayor, and M. Arndt, Nature Phys. 3, 711 – 715 (2007).
[2] K. Hornberger, S. Gerlich, P. Haslinger, S. Nimmrichter and M. Arndt, Rev. Mod. Phys. 84, 157–173 (2012)
[3] S. Eibenberger, S. Gerlich, M. Arndt, M. Mayor, and J. Tüxen, Phys. Chem. Chem. Phys. 15, 14696-14700 (2013).
[4] M. Berninger, A. Stefanov, S. Deachapunya, and M. Arndt, Phys. Rev. A 76, 013607 (2007).
[5] S. Eibenberger, S. Gerlich, M. Arndt, J. Tüxen, and M. Mayor, New J. Phys. 13, 043 033 (2011).
[6] S. Eibenberger, X. Cheng, J.P. Cotter, M. Arndt, arXiv:1402.5307 [quant-ph]

Atom interferometry of trapped BECs with tunable interactions

Andreas Trenkwalder[1], Giacomo Spagnolli[1], Giacomo Colzi[1], Giulia Semeghini[1], Manuele Landini[1], Giovanni Modugno[1, 2], Massimo Inguscio[1, 2], Marco Fattori[1, 2]

1. LENS and Dipartimento di Fisica e Astronomia, Universita di Firenze, and Istituto Nazionale di Ottica, CNR, 50019 Sesto Fiorentino, Italy
2. INFN, Sezione di Firenze, 50019 Sesto Fiorentino, Italy

We present a new atom interferometry experiment with BECs of 39K atoms with tunable interactions. The setup consists of an array of double-well potentials which we can operate in parallel. The tunability of interactions allows to obtain long coherence times and the possibility of using entangled states has the potential to increase the sensitivity beyond shot noise towards the Heisenberg limit.

Precision Measurements and Fundamental Tests Tu-125

Generation 2 of the ACME electron EDM search

Jacob Baron[1], David DeMille[2], John Doyle[1], Gerald Gabrielse[1], Paul Hess[1], Nicholas Hutzler[1], Emil Kirilov[3], Brendon O'Leary[2], Cristian Panda[1], Elizabeth Petrik[1], Ben Spaun[1], Adam West[2]

1. Harvard University
2. Yale University
3. University of Innsbruck

We present a proposal to upgrade the ACME experiment to make a new measurement of the electron’s electric dipole moment (eEDM). We plan a number of improvements to increase statistical sensitivity and suppress known systematic effects. Statistical sensitivity improvements include an upgraded molecular beam source, a molecular electrostatic guide, and a coherent state preparation scheme. We estimate a signal sensitivity improvement of at least an order of magnitude over our previous limit [1].

References

[1] The ACME Collaboration, Science 343, 269-272 (2014).

Precision Measurements and Fundamental Tests Tu-126

Measuring the Xe-129 Permanent Electric Dipole Moment

Skyler Degenkolb, Tim Chupp, for the XeEDM Collaboration

1. University of Michigan, Ann Arbor

We describe a new, ongoing measurement of the permanent electric dipole moment of the Xe-129 nucleus. Our technique, which extends sensitivity to beyond-Standard-model physics and makes Xe-129 available as a magnetometer species for other experiments, employs a cohabiting He-3 magnetometer and a magnetic environment with the lowest residual field and gradients yet produced over a cubic-meter volume.

The noble gas nuclear spins are prepared by spin-exchange optical pumping, and probed using sensitive magnetometry in a highly stable magnetic environment with both active and passive shielding. Novel cell design, magnetic shielding, SQUID detection, and next-generation optical magnetometry are discussed.

Cold and intense sources of large and heavy molecules for precision measurement of the electron EDM and parity violation

R.J. Hendricks[1], E.A. Hinds[1], M.R. Tarbutt[1], S.K. Tokunaga[2], B. Darquié[2]

1. Centre for Cold Matter, Blackett Laboratory, Imperial College London, UK
2. Laboratoire de Physique des Lasers, Université Paris 13, CNRS, F-93430, Villetaneuse, France

Measurements of heavy polar molecules, such as YbF, enable a very precise determination of the electic dipole moment of the electron [1]. Here we describe new cryogenic buffer gas sources that we have developed, which provide beams of molecules that are significantly slower and more intense than the supersonic beams used previously [2]. The use of such a buffer gas beam, in combination with laser cooling, is expected to reduce the statistical uncertainty of measurements of the electron EDM being carried out at Imperial College London by several orders of magnitude [3].

Similarly, polyatomic molecules possessing chirality can be used to carry out sensitive and direct tests of parity violation. Recent proposals for such experiments have suggested that chiral derivatives of methyltrioxorhenium (CH_3ReO_3), or MTO, can be particularly sensitive probes of parity violation [4,5]. We have developed a simple source of buffer gas cooled MTO molecules in a closed cryogenic cell. To demonstrate the low temperatures achieved, we have carried out high-resolution spectroscopy of the Re-O antisymmetric stretching band at 10.2µm. We will present these results, along with plans to build a slow and intense beam of buffer gas cooled MTO molecules for use in a measurement of parity violation.

References

[1] J.J. Hudson et al., Nature 473, 493-496 (2011)
[2] N.E. Bulleid et al., Phys. Chem. Chem. Phys. 15, 12299 (2013)
[3] M.R. Tarbutt et al., New J. Phys. 15, 053034 (2013)
[4] C. Stoeffler et al., Phys. Chem. Chem. Phys. 13, 854 (2011)
[5] N. Saleh et al., Phys. Chem. Chem. Phys. 15, 10952 (2013)

Interrogating the atomic nucleus with laser spectroscopy: francium (Fr) hyperfine anomaly and isotope shift measurements.

Jiehang Zhang[1], Michael Tandecki[2], Robert Collister[3], Seth Aubin[5], John Behr[2], Eduardo Gomez[4], Gerald Gwinner[3], Luis Orozco[1], Matthew Pearson[2], Gene Sprouse[6]

1. *Joint Quantum Institute, Department of Physics, University of Maryland at College Park, MD 20742, USA.*
2. *TRIUMF, Vancouver, BC V6T2A3, Canada*
3. *Dept. of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T2N2, Canada*
4. *Instituto de Física, Universidad Autónoma de San Luis Potosí, San Luis Potosí 78290, México*
5. *Department of Physics, College of William and Mary, Williamsburg VA 2319, USA.*
6. *Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800, USA.*

We present laser spectroscopy of francium. The experiment uses laser cooling and trapping techniques in an accelerator-based radioactive isotope facility at TRIUMF, Canada. We use RF modulation techniques to carry out precise measurements of $7P_{1/2}$ state (*D1* line) hyperfine splitting in isotopes $^{206\text{-}213}$Fr and ^{221}Fr, including the long-lived isomer of ^{206}Fr, we observe the effect of the spatial distribution of the neutron magnetization: the hyperfine anomaly (Bohr-Weisspkof effect). This measurement provides a sensitive probe of the neutron wavefunction for testing theories near the doubly "magic" ^{208}Pb region. The isotope shift with its sensitivity to electron correlations is used to benchmark *ab-ibitio* atomic theory calculations. These important tests for both the atomic and nuclear theory are needed for extracting weak interaction parameters from atomic parity non-conservation (APNC) measurements. Supported by NRC, TRIUMF, and NSERC from Canada, DOE and NSF from the USA, and CONACYT from Mexico.

Precision Measurement of Li Hyperfine & Fine Structure Intervals

William van Wijngaarden, Hang Yang, Bin Jian

1. Physics Department, York University

A number of experiments have precisely measured fine and hyperfine structure splittings as well as isotope shifts for several transitions at optical frequencies for ^{6,7}Li [1]. These data offer an important test of theoretical techniques developed by two groups to accurately calculate effects due to QED and the finite nuclear size in 2 and 3 electron atoms. The work by multiple groups studying several transitions in both Li^+ and neutral Li permits a critical examination of the consistency of separately, the experimental work as well as theory. Combining the measured isotope shifts with the calculated energy shifts passing these consistency tests permits the determination of the relative nuclear charge radius with an uncertainty approaching 1 x 10^{-18} meter which is more than an order of magnitude better than obtained by electron scattering. Propsects for a precision measruement of the fine structure constant are also discussed.

References

[1] W. A. van Wijngaarden & B. Jian, European Physical Journal D, 222, 2057-2066 (2013)

Nuclear Spin Dependent Parity Violation in Diatomic Molecules

Emine Altuntas[1], Jeffrey Ammon[1], Sidney B. Cahn[1], Yulia Gurevich[1], David DeMille[1], Richard Paolino[2], Mikhail G. Kozlov[3]

1. Yale University
2. U.S. Coast Guard Academy
3. Petersburg Nuclear Physics Institute

Nuclear spin-dependent parity violation (NSD-PV) effects arise from exchange of the Z^0 boson between electrons and the nucleus, and from interaction of electrons with the nuclear anapole moment (a parity-odd magnetic moment induced by electroweak interactions within the nucleus). We study NSD-PV effects using diatomic molecules. Here, observable signals from NSD-PV are amplified by many orders of magnitude when two levels of opposite parity are brought close to degeneracy in a strong magnetic field. We present preliminary results that demonstrate statistical sensitivity to NSD-PV effects surpassing that of any previous atomic parity violation measurement, using the test system ^{138}Ba^{19}F. We also discuss systematic errors in the current measurements, and short-term prospects for measuring the nuclear anapole moment of ^{137}Ba with this method. Over the long term, our technique is sufficiently general and sensitive that it should apply to measurements of the NSD-PV couplings for a wide range of nuclei.

Shifts due to quantum-mechanical interference from distant neighboring resonances

A. Marsman[1], M. Horbatsch[1], E. A. Hessels[1]

1. York University, Toronto, Canada

Quantum-mechanical interference with distant neighboring resonances is found to cause shifts for precision saturated fluorescence spectroscopy of the atomic helium $2\ ^3S$-to-$2\ ^3P$ transitions. The shifts are significant (larger than the experimental uncertainties for measurements of the intervals) despite the fact that the neighboring resonances are separated from the measured resonances by 1400 and 20000 natural widths. The shifts depend strongly on experimental parameters such as the angular position of the fluorescence detector and the intensity and size of laser beams. These shifts must be considered for the ongoing program of determining the fine-structure constant from the helium $2\ ^3P$ fine structure. The work represents the first study of such interference shifts for saturated fluorescence spectroscopy and follows up on our previous study of similar shifts for laser spectroscopy.

This work is supported by NSERC, CRC, ORF, CFI, NIST and SHARCNET.

Buffer gas cells and quantum cascade lasers: towards measuring parity violation in chiral molecules using vibrational spectroscopy

Sean K. Tokunaga[1, 2], Alexander Shelkovnikov[1, 2, 3], Papa Lat Tabara Sow[1, 2], Sinda Mejri[1, 2], Olivier Lopez[1, 2], Andrey Goncharov[1, 2, 4], Bérengère Argence[1, 2], Christophe Daussy[1, 2], Anne Amy-Klein[1, 2], Christian Chardonnet[1, 2], Benoît Darquié[1, 2], Richard J. Hendricks[5], Ed A. Hinds[5], Mike R. Tarbutt[5]

1. *CNRS, UMR 7538, LPL, 93430 Villetaneuse, France*
2. *Université Paris 13, Sorbonne Paris Cité, Laboratoire de Physique des Lasers, 93430 Villetaneuse, France*
3. *P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia*
4. *Institute of Laser Physics of SB RAS, Pr. Lavrentyeva 13/3, Novosibirsk, 630090 Russia*
5. *Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, UK*

The weak interaction should cause parity violating frequency shifts between the rovibrational spectra of two enantiomers of a chiral molecule. However, these effects have never been observed. We report on our latest progress towards making this observation.

On the source side, we report the creation of an 8 K buffer gas cell of methyltrioxorhenium (MTO), a molecule of interest for the project. An MTO target is ablated in the cell using an Nd:YAG laser, and the resulting plume is cooled by the helium buffer gas. This is the first buffer gas cell of organometallic molecules, and is a stepping-stone towards a key goal of making a beam.

We also report the locking of a 10μm QCL onto our narrow linewidth CO_2 laser. The result is a QCL with a 10 Hz linewidth, the narrowest to date [1].

References

[1] P.L.T. Sow, S. Mejri, S.K. Tokunaga, O. Lopez, A. Goncharov, B. Argence, C. Chardonnet, A. Amy-Klein, C. Daussy, B. Darquié, App. Phys. Lett., in press (2014), arXiv:1404.1162

Progress in barium tagging for the next generation ^{136}Xe double beta decay experiment

Tim Walton[1], Chris Chambers[1], Adam Craycraft[1], William Fairbank[1], the EXO Collaboration

1. Physics Department, Colorado State University, Fort Collins CO 80523

The "ideal" next-generation neutrinoless double beta decay experiment would have tonne-scale mass and perfect discrimination against all background events. This is uniquely conceivable in a liquid or gas ^{136}Xe double beta decay experiment through detecting, or "tagging", the ^{136}Ba daughter atom or ion at the site of the decay.[1],[2] The next-generation ^{136}Xe experiment, nEXO, could probe the region of normal neutrino mass hierarchy with the implementation of barium daughter tagging in its second stage of operation.

Within the EXO Collaboration, efforts to demonstrate barium atom tagging in liquid xenon include using laser fluorescence of single Ba atoms captured in solid xenon on an optical probe and thermal ionization or laser ablation and resonance ionization of single Ba atoms captured on a tip. Barium tagging research in xenon gas includes extraction of single Ba ions from high pressure Xe gas and transport to an ion trap.

Supported by NSF and DOE.

References

[1] M.K. Moe, Phys. Rev. C 44, R931 (1991).
[2] D. Akimov, et al., Nuclear Physics B (Proc. Suppl.) 138, 224 (2005).

Precision Measurements and Fundamental Tests Tu-134

Towards an improved measurement of the n=2 triplet P fine structure of helium

K. Kato[1], T. D. G. Skinner[1], M. Weel[1], A. C. Vutha[1], C. H. Storry[1], M. C. George[1], E. A. Hessels[1]

1. York University, Toronto, Canada

A comparison of precise experimental and theoretical determinations of the n=2 triplet P fine structure of helium allows for a precise determination of the fine-structure constant. An improved experiment is in progress which uses transverse laser cooling to prepare a more intense beam of thermal metastable helium atoms. Fine-structure transitions are driven using microwaves in a separated-oscillatory-field configuration. A new detection technique via an intermediate transition to the 3S state eliminates the largest systematic effect in our previous measurement and improves the signal-to-noise ratio.

We acknowledge funding from NSERC, CFI, CRC, ORF, and NIST.

Neutrino spectroscopy with atoms and molecules

Takahiko Masuda, for the SPAN collaboration

1. Research Core for Extreme Quantum World, Okayama University

This poster describes a new experimental method using atoms and molecules which is aiming at the measurement of unknown parameters of neutrinos: the absolute mass, the particle type (Majorana or Dirac), and the CP-violating phases. The process we use is a cooperative de-excitation of a collective body of atoms in a metastable level emitting a neutrino pair associated with a photon. An observable of this experiment is wavelength of the photon which is emitted with a neutrino pair, and the spectra of the photon have information of the neutrino properties. One important item of this experiment is the amplification of emission rate using macro-coherence in target media. We thus performed an experiment to validate this amplification mechanism with para-hydrogen gas target and two monochromatic lasers. The experimental concept of neutrino spectroscopy, expected spectra of photon energy, and the current status of the experiment will be discussed.

The Cold Atom Gravimeter at the μ-Gal-Level for Field Applications

Zhaoying Wang[1], Bing Cheng[1], Bin Wu[1], Aopeng Xu[1], Qiyu Wang[1], Xiaolong Wang[1], Qiang Lin[1]

1. Institute of Optics, Department of Physics, Zhejiang University

Recently, the novel inertial sensors based on atom interferometer have a rapid development. The mobile atom gravimeter has become a reality. We have realized a high precision atom gravimeter for field applications. Currently, with the interrogation time and the repetition rate 2.2 Hz, a sensitivity of has been reached in our experiment. The tidal phenomenon is observed continuously over 128 h based on our atom gravimeter. Moreover, a whole seismic wave occurred in Pakistan was recorded in detail with our atom gravimeter and the results are very consistent with that recorded by a traditional seismic detector. Finally□the absolute gravity value at the location of our laboratory has been measured, the uncertainty of the measurement is about . The current performance of our gravimeter meets the most of the field applications.

Critical Nuclear Charge and Electron Charge Distribution for Two-Electron Atoms

Gordon Drake[1], Camille Estienne[2], Michael Busuttil[1], Travis Valdez[1]

1. Department of Physics, University of Windsor, Windsor, ON Canada N9B 3P4
2. Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany

The critical nuclear charge Z_c required to bind a nucleus plus two electrons in a heliumlike atom has been calculated to high precision, thereby resolving a long-standing discrepancy in the literature [1]. The result is $Z_c = 0.911028224077255\,73(4)$, corresponding to $1/Z_c = 1.0976608337385\,5980(5)$. The outer electron remains localized near the nucleus, even at $Z = Z_c$, and the bound state evidently changes smoothly into a shape resonance for $Z < Z_c$. A qualitative polarization potential is proposed to account for the resonance, and the radial distribution function for the electron density is calculated.

References

[1] C. Estienne et al., Phys. Rev. Lett., 112, 173001 (20140).

ATOMIC CLOCKS

Progress Toward a Spin Squeezed Optical Atomic Clock Beyond the Standard Quantum Limit

Boris Braverman[1], Akio Kawasaki[1], Vladan Vuletić[1]

1. Department of Physics, MIT-Harvard Center for Ultracold Atoms and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

State of the art optical lattice atomic clocks have reached a relative inaccuracy level of 10^{-18} [1,2], already making them the most stable time references in existence. One restriction on the precision of these clocks is the projection noise caused by the measurement of the atomic state. This limit, known as the standard quantum limit (SQL), can be overcome by entangling the atoms. By performing spin squeezing [3], it is possible to robustly generate such entanglement and therefore surpass the SQL of precision in optical atomic clocks [4]. I will report on recent experimental progress toward realizing spin squeezing in an ^{171}Yb optical lattice clock. A high-finesse micromirror-based optical cavity mediates the atom-atom interaction necessary for generating the entanglement. By exceeding the SQL in this state of the art system, we are aiming to advance precision time metrology and expand the boundaries of quantum control and measurement.

References

N. Hinkley et al., Science 341, 1215 (2013)
B.J. Bloom et al., Nature 506 71 (2014)
M. Kitagawa et al., Phys. Rev. A 47, 5138 (1993)
I.D. Leroux et al., Phys. Rev. Lett. 104, 250804 (2010)

Near-Heisenberg-Limited Atomic Clocks in the Presence of Decoherence

Johannes Borregaard[1], Anders S. Sørensen[1]

1. QUANTOP, The Niels Bohr Institute, University of Copenhagen

The ultimate stability of atomic clocks is limited by the quantum noise of the atoms. To reduce this noise it has been suggested to use entangled atomic ensembles with reduced atomic noise. Potentially this can push the stability all the way to the limit allowed by the Heisenberg uncertainty relation, which is denoted the Heisenberg limit. In practice, however, entangled states are often more prone to decoherence, which may prevent reaching this performance. We present an adaptive measurement protocol that in the presence of a realistic source of decoherence enables us to get near-Heisenberg-limited stability of atomic clocks using entangled atoms. The protocol may thus realize the full potential of entanglement for quantum metrology despite the detrimental influence of decoherence [1].

References

[1] J. Borregaard and A. S. Sørensen, Phys. Rev. Lett. 111, 090801 (2013)

Hunting for topological dark matter with atomic clocks

Andrei Derevianko[1], Maxim Pospelov[2]

1. University of Nevada, Reno, USA
2. Perimeter Institute and University of Victoria, Canada

The cosmological applications of atomic clocks so far have been limited to searches of the uniform--in--time drift of fundamental constants. Here we point out that a transient in time change of fundamental constants can be induced by dark matter objects that have large spatial extent, and are built from light non--Standard Model fields. The stability of this type of dark matter can be dictated by the topological reasons.

We point out that correlated networks of atomic clocks, some of them already in existence (e.g., GPS), can be used as a tool to search for the topological defect dark matter, thus providing another important fundamental physics application to the ever-improving accuracy of atomic clocks. During the encounter with a topological defect, as it sweeps through the network, initially synchronized clocks will become desynchronized. Time discrepancies between spatially separated clocks are expected to exhibit a distinct signature, encoding defect's space structure and its interaction strength with the Standard Model fields.

References

A.Derevianko and M. Pospelov, arXiv:1311.1244

Atomic Clocks Tu-141

Trapping Ra$^+$: Optical Clock and Atomic Parity Violation

Elwin A. Dijck, Mayerlin Nuñez Portela, Amita Mohanty, Nivedya Valappol, Andrew T. Grier, Oliver Böll, Steven Hoekstra, Klaus Jungmann, Gerco Onderwater, Rob G. E. Timmermans, Lorenz Willmann, Hans W. Wilschut

1. Van Swinderen Institute, University of Groningen, The Netherlands

We study single trapped Ra$^+$ ions for a precision measurement of the Weinberg angle at low energy, testing the electroweak running. Ra$^+$ has the largest atomic parity violation effect for a simple electronic structure. In addition, the electric quadrupole transitions 7s $^2S_{1/2}$ – 6d $^2D_{3/2}$ at 828 nm and 7s $^2S_{1/2}$ – 6d $^2D_{5/2}$ at 728 nm to the low-lying metastable D-states of Ra$^+$ are excellently suited for an optical clock. In specific radium isotopes the lack of a linear Zeeman and/or electric quadrupole shift promises a robust clock operating at a relative uncertainty level of 10^{-18} [1]. The heavy Ra$^+$ ion is sensitive to a changing fine structure constant and has easily accessible transition wavelengths. Relevant transitions have been studied using laser spectroscopy of short-lived Ra$^+$ [2] and current experiments are focused on trapping single Ba$^+$ ions as precursor to Ra$^+$. Work toward single ion trapping of Ra$^+$ is in progress.

References

[1] O. O. Versolato et al., Phys. Rev. A 83, 043829 (2011)
[2] M. Nuñez Portela et al., Appl. Phys. B 114, 173 (2014)

Atomic Clocks Tu-142

Sorting ions in an two-species ion chain by amplitude-modulated laser beams for a new In$^+$ optical clock

Nozomi Ohtsubo[1], Ying Li[1], Kensuke Matsubara[1], Tetsuya Ido[1], Kazuhiro Hayasaka[1]

1. National Institute of Information and Communications Technology

We have proposed a new implementation of an In$^+$ optical clock based on In$^+$ ions sympathetically cooled with Ca$^+$ ions in a linear trap [1]. This implementation can be extended to a multi-ion clock with enhanced stability, provided that In$^+$ and Ca$^+$ can be sorted in proper orders. Sorting ions in a non-segmented trap is not a trivial task, but this might be possible by selectively destabilizing undesired orders. Different eigenmode frequencies of collective motion of ions dependent on the ion order enable the selective destabilization by a laser beam with amplitude modulation at the eigenfrequencies. Once the order is changed to the desired order by destabilization, the ion chain doesn't interact with the AM frequency anymore and stays as it is. A principle of proof experiment is successfully demonstrated with an ion chain consisting of two Ca$^+$ and one In$^+$. The status of In$^+$ clock development is also reported.

References

[1]K. Haysaka, Appl. Phys. B. 107, 965 (2012).

Agile coherent control of ions in a microfabricated trap

Joseph Thom[1, 2], Guido Wilpers[1], Erling Riis[2], Alastair Sinclair[1]

1. *National Physical Laboratory, London, UK, TW11 0LW*
2. *University of Strathclyde, Glasgow, UK, G4 0NG*

Using an agile laser system [1], we have demonstrated coherent control on the $S_{1/2}$ – $D_{5/2}$ optical qubit transition (674 nm) of $^{88}Sr^+$ ions confined in our microfabricated ion trap [2]. We use amplitude-shaped pulses to minimise off-resonant excitation of other Zeeman transitions in the ion's spectrum. When combined with the laser's phase agility, this enables tailoring of the spectral lineshape in Rabi and Ramsey excitations. A spin echo sequence was used to demonstrate an improved coherence time over our previous work. Frequency-resolved optical pumping on the 674 nm transition has also been investigated, and resolved sideband cooling of the ion's motional modes is in progress. This agile coherent control will be used to implement the Mølmer - Sørensen entangling gate [3,4] on $^{88}Sr^+$. Entangled states in the microfabricated trap will be used to explore applications in quantum metrology experiments.

References

[1] J. Thom, et.al, Opt. Express 21, 18712 (2013).
[2] G. Wilpers, et.al, Nature Nanotech. 7, 572 (2012).
[3] A. Sørensen and K. Mølmer, Phys. Rev. Lett. 82, 1971 (1999).
[4] J. Benhelm, et. al, Nature. Phys. 4, 463 (2008).

Highly-charged ions for atomic clocks, quantum information, and search for α-variation

M. S. Safronova[1, 2], V. A. Dzuba[3], V. V. Flambaum[3], U. I. Safronova[4, 5], S. G. Porsev[1, 6], M. G. Kozlov[6, 7]

1. University of Delaware, Newark, Delaware, USA
2. Joint Quantum Institute, NIST and the University of Maryland, College Park, Maryland, USA
3. University of New South Wales, Sydney, Australia
4. University of Nevada, Reno, Nevada, USA
5. University of Notre Dame, Notre Dame, Indiana, USA
6. Petersburg Nuclear Physics Institute, Gatchina, Russia
7. St. Petersburg Electrotechnical University, "LETI'', St. Petersburg, Russia

We propose 10 highly-charged ions as candidates for the development of next generation atomic clocks, quantum information, and search for α-variation. These are the only highly-charged ions that have the long-lived metastable states with transition frequencies to the ground state between 170-3000 nm, relatively simple electronic structure, high sensitivity to α-variation, and stable isotopes. We find that only the ions in four isoelectronic sequences, Ag-like, Cd-like, In-like, and Sn-like satisfy these criteria. We predict their properties crucial for the experimental exploration. We find that Pr^{+9} ion is a particular attractive candidate for these applications as it possesses a unique metastable level structure with optical transitions not present in any neutral and low-ionization state systems. Highly-charged ions are less sensitive to external perturbations than either neutral atoms or singly-charged ions due to their more compact size, potentially leading to reduced decoherence effects and smaller ultimate clock uncertainties.

High power, very narrow linewidth, micro-integrated diode laser modules designed for quantum sensors in space

Anja Kohfeldt[1], Christian Kürbis[1], Erdenetsetseg Luvsandamdin[1], Max Schiemangk[1, 2], Andreas Wicht[1, 2], Götz Erbert[1], Achim Peters[1, 2], Günther Tränkle[1]

1. Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany

2. Humboldt-Universität zu Berlin, Institut für Physik, Newtonstraße 15, 12489 Berlin, Germany

We report on the development of very robust, energy efficient, micro-integrated Master-Oscillator-Power-Amplifier (MOPA) and Extended-Cavity-Diode-Laser (ECDL) modules for the deployment of cold atom based quantum sensors in space. The micro-optical benches, not larger than 80x25 mm^2, include an electrical interface that allows for high modulation bandwidth, a feature especially useful for spectroscopy applications. With MOPAs and ECDLs designed for rubidium BEC and atom interferometry experiments at 780 nm we achieved an intrinsic linewidth of 35 kHz at 1.4 W and of 2 kHz at 35 mW, respectively. Due to individual temperature control of the external Bragg grating ECDLs can be tuned continuously by more than 30 GHz [1] . The technology can be transferred to all wavelengths accessible by laser diodes, e.g. 767 nm [2] for spectroscopy with potassium.

References

[1] E. Luvsandamdin et al., Appl. Phys. B 111, 255-260 (2013)

[2] E. Luvsandamdin et al, Opt. Express 22, 7790-7798 (2014)

Towards a fully-miniaturised magneto-optical trap system for portable ultracold quantum technology

Matthew Aldous[1]

1. University of Southampton

We present progress on work carried out in the development of enabling technologies for integrated atom chips [1]. Cold atom experiments have flourished with the advent of atom chips, whose construction readily lends itself to integration with larger systems and future mass production. To bring these experiments out of the lab and make use of them in new settings, the complex surrounding infrastructure (including vacuum systems, optics, and lasers) also needs to be miniaturized and integrated. The ideal solution would seem to be an Integrated Atom Chip incorporating the vacuum system, atom source and optical geometry into a permanently sealed micro-litre system capable of maintaining 10^{-10} mbar for more than 1000 days of operation with no active pumping systems. The primary focus of the project so far has been on the design and construction of a silicon die bonding system capable of producing such devices with high longevity and hermeticity.

References

[1] J. Rushton, M. Aldous, and M. Himsworth, "The Feasibility of a Sealed and Miniaturized Magneto-Optical Trap for Portable Ultracold Quantum Technology," 2014.

Locking Raman laser frequency of up to 40 GHz offset for atom interferometers

Jin Wang[1, 2], Wencui Peng[1, 2, 3], Lin Zhou[1, 2], Shitong Long[1, 2, 3], Mingsheng Zhan[1, 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*
2. *Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071*
3. *University of the Chinese Academy of Sciences, Beijing 100049*

Laser frequency stabilization is widely used in the study of atomic and molecular physics [1, 2], measurements of fundamental physical constants [3, 4], and precision spectroscopy [5]. Optical phase locked loops (OPLLs) allow one laser to track another with a fixed frequency difference and a maximum tuning range of 40 GHz [6]. We demonstrate a method to lock a laser frequency of up to 40 GHz offset to a reference using a 10 GHz electro-optic modulator (EOM) [7]. Offsetting is provided by the EOM sidebands, and first- to fourth-order sidebands are generated by changing the power of the EOM's driving frequency. By scanning the driving frequency across the 10 GHz bandwidth, the output laser frequency can be tuned over an 80 GHz range (−40 to 40 GHz) by locking a sideband to the reference. This method provides simple, stable, and low-cost generation of Raman laser pairs for atom interferometers.

References

[1] J. C. Camparo, Phys. Rev. Lett. 80, 222 (1998).
[2] S. K. Tokunaga, C. Stoeffler, F. Auguste, A. Shelkovnikov, C. Daussy, A. Amy-Klein, C. Chardonnet, B. Darquie, Mol. Phys. 111, 2363 (2013).
[3] R. Bouchendira, P. Clade, S. Guellati-Khelifa, F. Nez, F. Biraben, Phys. Rev. Lett. 106, 080801 (2011).
[4] G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, G. M. Tino, Phys. Rev. Lett. 100, 050801 (2008).
[5] T. M. Fortier, Y. Le Coq, J. E. Stalnaker, D. Ortega, S. A. Diddams, C. W. Oates, L. Hollberg, Phys. Rev. Lett. 97, 163905 (2006).
[6] K. Numata, J. R. Chen, S. T. Wu, Opt. Express 20, 14234(2012).
[7] W. C. Peng, L. Zhou, S. T. Long, J. Wang, and M. S. Zhan, Opt. Lett. 39, 2998 (2014).

Optical phase locking of two extended-cavity diode lasers : direct modulation and serrodyne modulation

Sin Hyuk Yim[1], Sang Eon Park[2], Sang Bum Lee[2], Taeg Yong Kwon[2]

1. Agency for Defense Development
2. Korea Reseach Institute of Standards and Science

We present two methods for optical phase locking of two extended-cavity diode lasers with ultra low phase noise. The frequency difference between two lasers is 6.9 GHz, which is close to the ground-state hyperfine splitting of ^{87}Rb. First method is a direct modulation scheme, where the phase error signal is electrically fedback to the injection current of a slave laser. Second method is a serrodyne modulation scheme, where the phase error signal is fed into an electro-optic modulator after the slave laser. In both cases, the bandwidth of the optical phase locking loop is extended up to 8 MHz and the residual phase noise of two phase-locked lasers reaches below -120 dBrad^2/Hz in the offset frequency range of 100 Hz to 300 kHz. These schemes will be employed to enhance the sensitivity limit in atom interferometer.

References

[1] S. H. Yim, S. B. Lee, T. Y. Kwon, and S. E. Park, Appl. Phys. B. (2013).
[2] M. Kasevich, D. S. Weiss, E. Riis, K. Moler, S. Kasapi, and S. Chu, Phys. Rev. Lett. 66, 2297 (1991).
[3] M. Schmidt, M. Prevedelli, A. Giorgini, G. M. Timo, and A. Peters, Appl. Phys. B. 102, 11 (2011).

A Dynamic Magneto-Optical Trap for Atom Chips

Joseph Rushton, James Bateman, Matthew Himsworth

1. University of Southhampton

We demonstrate a new mirror magneto-optical trap which relies on time varying optical and magnetic fields in an analogous configuration to the quadrupole ion trap. The AC operation of the trap removes the requirement of an in plane laser beam seen in other mirror MOTs, and as a result is advantageous in applications where optical access is restricted to a single window. Due to the planar nature of this design it is particularly well suited for use in atom chips, and unlike some other traps this dynamic MOT works independently of the wavelength of the light used, allowing for multiple atomic species to be trapped simultaneously.

Holographic Laguerre-Gaussian beams for long-distance channeling of a 2D-MOT generated cold atom beam.

Vincent Carrat[1, 2], Citlali Cabrera[2], Bruno Viaris de Lesegno[2], Marion Jacquet[2], Laurence Pruvost[2]

1. *Department of Physics, University of Virginia, Charlottesville, Virginia 22904-0714, USA*
2. *Laboratoire Aimé Cotton, CNRS, Univ. Paris Sud, ENS Cachan F 91405, Orsay, France*

A 2D-MOT is an efficient sources for cold atoms experiments. Unfortunately, the divergence (≈ 40 mrad) of the atom beam is problematic if the 2D-MOT has to be far from the main science area. We have demonstrated a reduction in the size of the beam from 12 mm to 1 mm 300 mm away from our 2D-MOT output by guiding the atomic beam in a blue detuned holographically generated Laguerre-Gaussian (LG) mode. As the atoms are guided in the dark center of the donut shaped LG beam, heating is low compared to a red detuned guide, allowing a longer guiding distance. Holography could generate in principle any laser beam shapes. As cold atoms are sensitive to perturbations, the generated light field must be precisely defined. Unfortunately, spatial light modulators (SLM) suffer from defects that need to be corrected for high-fidelity holography. We have also demonstrated an active and in-situ SLM correction.

References

[1] Vincent Carrat, Citlali Cabrera-Gutiérrez, Marion Jacquey, José W. Tabosa, Bruno Viaris de Lesegno, and Laurence Pruvost, Optics Letters, 39, 719-722 (2014).

[2] Vincent Carrat, Laurence Pruvost, Bruno Viaris de Lesegno, Liquid Crystals XVII, Iam Choon Khoo, Editors, Proceedings of SPIE 8828, 882812 (2013).

Boltzmann-Vlasov approach and Fermi surface anisotropy in dipolar Fermi gases

Vladimir Veljić[1], Antun Balaž[1], Axel Pelster[2]

1. Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

2. Department of Physics and Researech Center OPTIMAS, Technical University of Kaiserslautern, Erwin Schroedinger Street, Building 46, 67663 Kaiserslautern, Germany

We study harmonically trapped three-dimensional ultracold Fermi and Bose gases in the presence of the short-range contact and the long-range anisotropic dipole-dipole interaction. The dynamics of such quantum systems can be described by the Boltzmann-Vlasov equation. Dipole-dipole interaction breaks rotational symmetry in momentum space and gives rise to an elliptic Fermi surface. We calculate time-of-flight expansion all the way from in a collisionless to the hydrodynamic regime and show that momentum distribution is stretched along the orientation of dipoles, arising dominantly from the Fermi surface anisotropy. This result agrees with a recent experiment done in a collisionless regime by probing the momentum distribution of an atomic gas via time-of-flight expansion measurements.