Charles S. Adams, Durham University, Dept. of Physics, Durham, GB

**"Light transport in media with strong dipole-dipole interactions"**

Strong dipole-dipole interactions can dramatically modify the optical response of a medium and give rise to a non-equilibrium phase transition [1] or non-trivial propagation effects such as the conversion of classical light into quantum light [2,3] and resonant energy transfer (photon hopping) [3].

In this talk we consider the interaction of light with a one, two and many dipoles and discuss recent experiments on light propagation in atomic systems where the dipole-dipole interaction is manifest [1-5].

References:
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[2] T. Peyronel et al. Nature 488, 57 (2012).
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Francesco S. Cataliotti, LENS, IT

"**Atom Interferometry and Quantum State Reconstruction"**

Cold atomic systems and degenerate quantum gases are ideal playgrounds for the realization of quantum dynamics and the modeling of quantum systems. This is certainly due to the precise knowledge of the model Hamiltonian, the ability to manipulate its coupling constants, the possibility of working with controllable disorder that make an ultracold atomic system the ideal candidate for a Quantum Simulator [1]. However there is also another fundamental aspect that has to be considered to reach this goal; namely the development of techniques to fully characterize the quantum states realizable with ultracold atomic gases.
The means to extract information from cold atom systems are currently under vigorous development. The most commonly-used probes are a variant of time-of-flight (TOF) measurements: the atoms are released from their trapping potential and the cloud left to expand, falling under gravity. Alternatively, the atoms may be imaged before expansion, in which case a picture of the atom density profile in real space is obtained. Static second-order correlation functions can be obtained through statistical analysis of atom shot noise in the TOF images [1]. Alternatively, one may obtain both static and dynamic correlation functions by Bragg spectroscopy of the trapped atoms [3].
Powerful as they are all these methods are unable to fully reconstruct the quantum state of an atomic system in the same way that this is done in quantum optics. Recently a novel method directly inspired by optical homodyne techniques and based on atom interferometry was developed to reconstruct an atomic quantum state [4].
Matter-wave interferometry is a powerful tool for high-precision measurements of the quantum properties of atoms, many-body phenomena and gravity. The most precise matter-wave interferometers exploit the excellent localization in momentum space and coherence of the degenerate gases. Further enhancement of sensitivity and reduction of complexity are crucial conditions for success and widening of their applications. I will also discuss an original multi-state interferometric scheme that offers advances in both these aspects [5].

References:
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[3] R. Ozeri et al., *Rev. Mod. Phys.* **77**, 187 (2005); D. Clément, N. Fabbri, L. Fallani, C. Fort, and M. Inguscio, *Phys. Rev. Lett.* **102**, 155301 (2009).
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Ofer Firstenberg, Harvard Quantum Optics Center, US

“**Rydberg-mediated interaction between single slow-light photons**”

A 'probe' light field can be coherently coupled to high-lying Rydberg levels in an atomic gas by means of a second, stronger 'control' field. The control field induces a spectral transparency window in the otherwise opaque medium via electromagnetically induced transparency (EIT), and probe photons travel in the medium at a much reduced speed in the form of polaritons -- coupled excitations of light and matter. However, in contrast to conventional EIT, when two probe photons propagate simultaneously, the strong interaction between two Rydberg atoms tunes the transition out of resonance, thereby destroying the transparency and leading to absorption. This mechanism provides for strong anti-bunching of the probe photons. Tuning the process out of resonance reduces the nonlinear dissipation and increases the dispersion, resulting in a mutual phase-shift of photon pairs. Accordingly, the two-photon dynamics in the medium varies from diffusion-like to Schrodinger-like, where, for both cases, the effective interaction range is much larger than the blockade radius.

Reference:
“Quantum nonlinear optics with single photons enabled by strongly interacting atoms,”
(http://www.nature.com/nature/journal/v488/n7409/full/nature11361.html)
T. Peyronel, O. Firstenberg, Q.-Y. Liang, S. Hofferberth, A. V. Gorshkov, T. Pohl, M. D. Lukin, V. Vuletic, Nature (London) 488, 57-60 (2012).

Philippe Grangier, Institut d'Optique, Palaiseau, FR

**Rydberg blockade for manipulating atomic and photonic qubits**

We will present recent experiments using Rydberg blockade as a tool for either entangling atomic qubits [1, 2], or for creating very large optically non-linear effects [3] that could be applied to process photonic qubits [4] (see also related talks by Charles Adams and Ofer Firstenberg during this Winter School).

References:
[1] "Observation of collective excitation of two individual atoms in the Rydberg blockade regime", A. Gaetan et al, Nature Physics 5, 115 (2009)
[2] "Entanglement of Two Individual Neutral Atoms Using Rydberg Blockade", T. Wilk et al, Phys. Rev. Lett. 104, 010502 (2010)
[3] "Observation and Measurement of Interaction-Induced Dispersive Optical Nonlinearities in an Ensemble of Cold Rydberg Atoms", V. Parigi et al, Phys. Rev. Lett. 109, 233602 (2012)
[4] "Generating non-Gaussian states using collisions between Rydberg polaritons", J. Stanojevic et al, Phys. Rev. A 86, 021403 (2012)

Igor Lesanovsky, The University of Nottingham, GB

"**Spin physics with Rydberg atoms**"

Rydberg atoms in optical lattices constitute a versatile platform for the study of spin systems which has recently also been demonstrated experimentally.

In this theory lecture I will discuss the description of a strongly interacting Rydberg gas in terms of a spin ½ many-body Hamiltonian. I will show how dense Rydberg gases naturally realize quantum Ising and related models.

Specifically, I will discuss a parameter regime in which the Rydberg gas Hamiltonian is of so-called Rokhsar-Kievelson form. Here its ground state can be expressed as a quantum superposition of (classical) hard dimer configurations. This allows an analytical calculation of the ground state correlations and permits a detailed analysis of the melting of a Rydberg crystal under the influence of quantum fluctuations.

Papers for discussions:
- Many-body spin interactions and the ground state of a dense Rydberg lattice gas;
Physical Review Letters 106, 025301 (2011)
- Liquid ground state, gap and excited states of a strongly correlated spin chain;
Physical Review Letters 108, 105301 (2012)
- Interacting Fibonacci anyons in a Rydberg gas;
Physical Review A 86, 041601(R) (2012)
- Entropic enhancement of spatial correlations in a laser-driven Rydberg gas;
Physical Review A 86, 013408 (2012)

Robert Löw, Institute of Physics, University of Stuttgart, DE

**"Introduction to Rydberg atoms"**

In this school-type talk I will present the basic properties of Rydberg atoms, the methods to excite and to detect them. In the end I will extend the focus to ensembles of Rydberg atoms and their interactions.

**"Rydberg atoms in microscopic vapor cells"**

The strong interactions between Rydberg atoms can be employed in terms of an optical non-linearity. In our experiments we try to make use of these linearities to produce novel quantum optical devices. Our main focus lies on the realization of single photon source based on thermal atoms, but I will also discuss applications dedicated to sensing of micro-waves and probing surfaces.

Frédéric Merkt, ETH Zurich, CH

"**Manipulating Rydberg atoms and molecules in the gas phase and near chip surfaces**"

New experimental results on the manipulation of the translational motion of Rydberg atoms and molecules in the gas phase using inhomogeneous electric will be presented. In the experiments, cold atoms or molecules moving at high speed (about 700 m/s) in the laboratory reference frame in supersonic beams are photoexcited to Rydberg-Stark states with large electric dipole moments, deflected, slowed down to low velocity, and loaded in electric traps at translational temperature of about 100 mK. The talk will begin with an introduction on the properties of Rydberg states upon which these experiments rely.

Then, results on the deceleration and trapping of hydrogen atoms and molecules will be presented to illustrate the general principles of these experiments [1-3]. Blackbody-radiation-induced transitions and collisional processes limit the trapping times, but can be eliminated by maintaining the surfaces surrounding the Rydberg atom or molecule samples at 4 K after adiabatic $90^o$ deflection of the Rydberg atoms/molecules out of the supersonic beam.

Finally, experiments will be discussed in which (1) hydrogen Rydberg atoms have been decelerated and trapped above the surface of a chip [4], and (2) interactions between Rydberg atoms and on-chip transmission lines have been investigated spectroscopically [5].

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[1] S. D. Hogan and F. Merkt, Phys. Rev. Lett. **100**, 043001 (2008)
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[3] Ch. Seiler, S. D. Hogan, H. Schmutz, J. A. Agner and F. Merkt, Phys. Rev. Lett. **106**, 073003 (2011)
[4] S. D. Hogan, P. Allmendinger, H. Saßmannshausen, H. Schmutz and F. Merkt, Phys. Rev. Lett. **108**, Art. No. 063008:1–5 (2012)
[5] S. D. Hogan, J. A. Agner, F. Merkt, T. Thiele, S. Filipp and A. Wallraff, Phys. Rev. Lett. **108**, Art. No. 063004:1–5 (2012)

Beatriz Olmos Sanchez, University of Nottingham, GB

**Long-range interacting many-body systems with alkaline-earth-metal atoms**

Alkaline-earth-metal atoms exhibit long-range dipolar interactions, which are generated via the coherent exchange of photons on the 3P0-3D1-transition of the triplet manifold. In case of bosonic strontium, which we discuss here, this transition has a wavelength of 2.7 micrometers and a dipole moment of 2.46 Debye, and there exists a magic wavelength permitting the creation of optical lattices that are identical for the states 3P0 and 3D1. This interaction enables the realization and study of mixtures of hard-core lattice bosons featuring long-range hopping, with tuneable disorder and anisotropy. We derive the many-body Master equation, investigate the dynamics of excitation transport and analyze spectroscopic signatures stemming from coherent long-range interactions and collective dissipation. Our results show that lattice gases of alkaline-earth-metal atoms permit the creation of long-lived collective atomic states and constitute a simple and versatile platform for the exploration of many-body systems with long-range interactions. As such, they represent an alternative to current related efforts employing Rydberg gases, atoms with large magnetic moment, or polar molecules.

Tilman Pfau, Institute of Physics, University of Stuttgart, DE

"**Trilobites and other molecular animals: How Rydberg-electrons catch ground state atoms**"

We report on laser spectroscopy results obtained in a dense and frozen Rydberg gas. Novel molecular bonds resulting in ultralong-range Rydberg dimers were predicted [1] and dimers as well as trimers in different vibrational states were found [2]. Some of these states are predicted to be bound by quantum reflection. Lifetime measurements confirm this prediction. Coherent superposition between free and bound states have been investigated [3]. Recently we have also confirmed that in an electric field these homonuclear molecules develop a permanent dipole moment [4].

References:
[1] C. H. Greene, A. S. Dickinson, and H. R. Sadeghpour, *Phys. Rev. Lett.* **85**, 2458 (2000).
[2] V. Bendkowsky, B. Butscher, J. Nipper, J. P. Shaffer, R. Löw, T. Pfau, *Nature* **458**, 1005 (2009), V. Bendkowsky, B. Butscher, J. Nipper, J. Balewski, J. P. Shaffer, R. Löw, T. Pfau, W. Li, J. Stanojevic, T. Pohl, and J. M. Rost, *Phys. Rev. Lett.* **105**, 163201 (2010).
[3] B. Butscher, J. Nipper, J. B. Balewski, L. Kukota, V. Bendkowsky, R. Löw, and T. Pfau *Nature Physics* **6**, 970–974 (2010).
[4] W. Li, T. Pohl, J. M. Rost, Seth T. Rittenhouse, H. R. Sadeghpour, J. Nipper, B. Butscher, J. B. Balewski, V. Bendkowsky, R. Löw, T. Pfau, *Science* **334**, 1110 (2011).

Thomas Pohl, Max-Planck-Institute for the Physics of Complex Systems, Dresden, DE

**"Nonlinear Optics in cold Rydberg-EIT media"**

This talk will provide an overview of approaches to utilize strongly interacting Rydberg atoms for applications in nonlinear optics under conditions of electromagnetically induced transparency. Major emphasis will be placed the theoretical description of light propagation in such a strongly interacting Rydberg-EIT medium.

We will start by considering the dynamics of dark state polaritons in a conventional EIT setting, that allows to slow and even stop the propagation of light. This will serve as a basis for developing a theoretical framework to incorporate strong atomic interactions and to gain some basic intuition for their effects. To this end, we will first consider the propagation classical light, which permits to derive simple expressions for the arising optical nonlinearities. Using these insights, we then proceed with the quantum dynamics of few-photon light pulses under highly coherent as well as strongly dissipative conditions. Both cases are shown to open up promising perspective for optical quantum computing.

References:
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Peter Schauss, Max Planck Institute for Quantum Optics (MPQ), Garching, Germany

**“Observation of mesoscopic crystalline structures in a two-dimensional Rydberg gas”**

The ability to control and tune interactions in ultracold atomic gases has paved the way towards the realization of new phases of matter. Whereas experiments have so far achieved a high degree of control over short-ranged interactions, the realization of long-range interactions would open up a whole new realm of many-body physics and has become a central focus of research. Rydberg atoms are very well-suited to achieve this goal, as the van der Waals forces between them are many orders of magnitude larger than for ground state atoms. Consequently, the mere laser excitation of ultracold gases can cause strongly correlated manybody states to emerge directly when atoms are transferred to Rydberg states. A key example are quantum crystals, composed of coherent superpositions of different spatially ordered configurations of collective excitations. Here we report on the direct measurement of strong correlations in a laser excited two-dimensional atomic Mott insulator using high-resolution, in-situ Rydberg atom imaging. The observations reveal the emergence of spatially ordered excitation patterns in the high-density components of the prepared many-body state. They have random orientation, but well defined geometry, forming mesoscopic crystals of collective excitations delocalised throughout the gas. Our experiment demonstrates the potential of Rydberg gases to realise exotic phases of matter, thereby laying the basis for quantum simulations of long-range interacting quantum magnets.

Hendrik Weimer, Institute for Theoretical Physics, Leibniz University Hannover, Germany

**“Quantum Simulation with Rydberg Atoms”**

Simulating quantum many-body systems on classical computers is often an impossible task as the complexity of the problem grows exponentially with the system size. Universal quantum simulators -- controlled quantum devices that efficiently reproduce the dynamics of any other many particle quantum system -- could provide a way to overcome these obstacles.
I will present a theoretical proposal for the implementation of a universal quantum simulator based on ultracold Rydberg atoms [1,2] and I will discuss examples for the simulation of both coherent and dissipative dynamics.

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