YEA Meeting & Idea Factory

8-9 September 2014

Ultracold Rydberg Physics Workshop

10-12 September 2014

Book of Abstracts

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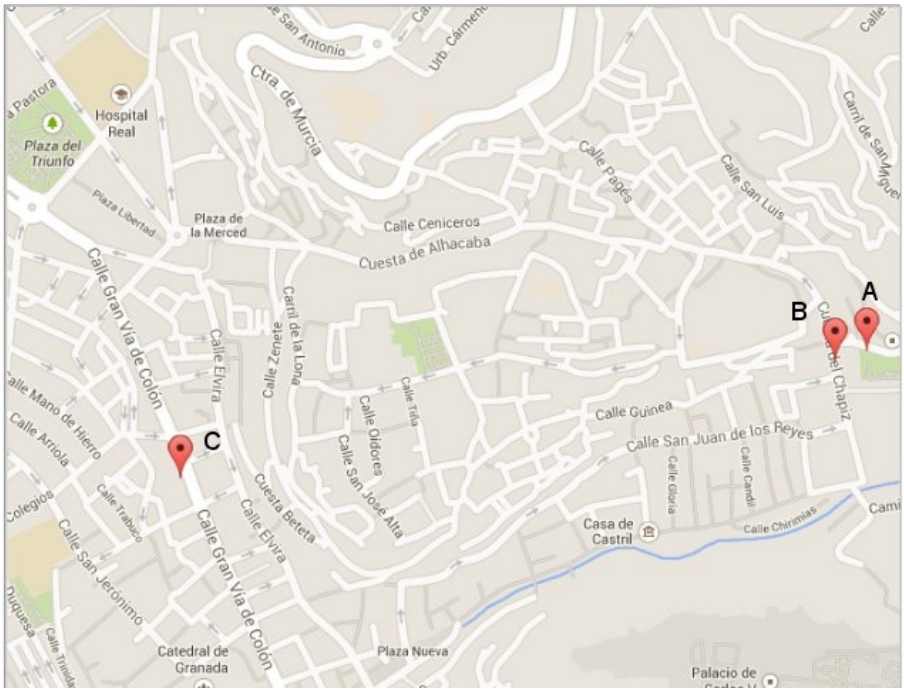
Practical information

- The YEA meeting and Idea Factory will be held at the "Carmen de la Victoria" (Cuesta del Chapiz 9, Granada 18010)
- The Ultracold Rydberg Atoms Workshop will be held at the Escuela de Estudios Arabes "Casas del Chapiz" (Cuesta del Chapiz 22, Granada 18010)
- Lunches and coffee breaks will take place at the "Carmen de la Victoria"
- The conference dinner will take place on Thursday September 12, at 20.30 at: Hotel AC Palacio de Santa Paula in Calle Gran Via de Colón 31

The main locations are displayed on the map below, **A** Escuela de Estudios Árabes, **B** Carmen de la Victoria and **C** Hotel AC Palacio de Santa Paula.



Wireless in the workshop venues

- eduroam network with your personal credentials
- In Carmen de la Victoria cviugr with login: phy@invitados.ugr.es
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YEA MEETING & IDEA FACTORY PROGRAM

Monday, September 8th

08:30 - 09:00 Registration at the "Carmen de la Victoria" (Cuesta del Chapiz 9, Granada)

09:00 - 09:45 Patrick Leisching
How to transfer concepts from R&D into marketing and advertising I

9:45 - 10:10 Anita Gaj
The latest news about ultralong-range Rydberg molecules

10:10 - 10:35 Markus Kurz
Ultralong-range Rydberg molecules in combined electric and magnetic fields

10:35 - 11:10 Coffee break

11:10 - 11:55 Oliver Morsch
Writing for different audiences: Colleagues, grants and the general public I

11:55 - 12:20 Miguel Ferreira-Cao
Dipolar exchange in interacting Rydberg gases

12:20 - 12:45 Hannes Busche
Microwave control of the interaction between two optical photons

12:45 - 13:10 Torsten Scholak
Spectral Signatures of Excitation Transport in Ultra-Cold Rydberg Gases

13:15 - 15:15 Lunch

15:15 - 16:00 Oliver Morsch
Writing for different audiences: Colleagues, grants and the general public II

16:00 - 16:25 Vladislav Gavryusev
Towards imaging of single Rydberg Atoms

16:25 - 16:50 Heiner Saßmannshausen
Observation of dipole-dipole and dipole-quadrupole interactions between pairs of ultracold Cesium Rydberg atoms

16:50 - 17:20 Coffee break

17:20 - 17:45 Rick Mukherjee
Coherent ion-transport via Rydberg dressing of an atomic optical lattice

17:45 - 18:10 Hossein Sadeghi
Formation of penning lattice in strongly correlated ultra-cold molecular plasma

18:10 - 18:35 Mike Kohlhoff
Collisional velocity dependence of hydrogen Rydberg atoms interacting with a surface

Tuesday, September 9th

09:00 - 09:45 Oliver Morsch
Writing for different audiences: Colleagues, grants and the general public III

09:45 - 10:10 Andreas Geißler
Dynamical Mean-Field Theory of Rydberg-dressed quantum gases in optical lattices

10:10 - 10:35 Marco Mattioli
Quantum 1-spin facilitated models with Rydberg atoms in optical lattices

10:35 - 11:10 Coffee break

11:10 - 11:55 Patrick Leisching
How to transfer concepts from R&D into marketing and advertising II

11:55 - 12:20 Wildan Abdussalam
Antiferromagnetic long-range order in dissipative Rydberg lattices

12:20 - 12:45 Alexander W. Glätzle
Quantum Ice and dimer models with ultra-cold Rydberg atoms and ions

12:45 - 13:10 Nikola Šibalić
Preparing highly excited states with pulsed ladder schemes in atom vapours at room temperature

13:15 - 15:15 Lunch

15:15 - 15:40 Johannes Zeiher
Dynamical crystallization in a low-dimensional Rydberg gas

15:40 - 16:05 Maarten L. Soudijn
Ultracold Atomic Ensembles on a Magnetic-Film Atom Chip for Quantum Information

16:05 - 16:30 Thanh Long Nguyen
Long coherence times for Rydberg qubits on a superconducting atom chip

16:30 - 17:00 Coffee break

17:00 - 17:25 Riccardo Faoro
Three-body Förster resonances in a frozen Rydberg gas

17:25 - 17:50 Henning Labuhn
Coherent dipole-dipole coupling between two single atoms at a Förster resonance

WORKSHOP PROGRAM

Tuesday, September 9th

19:00 - 21:00 Reception and registration at the "Carmen de la Victoria" (Cuesta del Chapiz 9, Granada)

Wednesday, September 10th

08:45 - 09:00 Opening

09:00 - 9:35 Thomas Killian
Strontium Ultracold Rydberg Gases

09:35 - 10:05 Matthew Jones
Rydberg blockade and dressing with Group II atoms

10:05 - 10:35 Russell Kliese
A Frequency Comb for Absolute Optical Frequency Measurement

10:35 - 11:10 Coffee break

11:10 - 11:45 Andreas Wallraff
Towards Hybrid Cavity Quantum Electrodynamics with Atoms and Circuits

11:45 - 12:20 Gerhard Rempe
From Rydberg switches to single-photon transistors

12:20 - 12:50 Mark Saffman
Rydberg mediated entanglement with trapped atoms

13:00 - 16:00 Lunch & Posters

16:00 - 16:30 Thierry Lahaye
Measuring dipole-dipole interactions between two single Rydberg atoms

16:30 - 17:00 Patrick Cheinet
Few-body interactions control in cold Rydberg atoms

17:00 - 17:30 Coffee break

17:30 - 18:00 Shannon Whitlock
Simulating dipolar energy transport with giant atoms

18:00 - 18:30 Sebastian Wüster
Towards quantum simulations of chemical and biological processes using ultra-cold Rydberg atoms

19:00 - 20:00 Supervisory Board Meeting

21:25 Meeting point: Plaza Nueva close to Iglesia Santa Ana

22:00 - 23:00 Alhambra visit

Thursday, September 11th

09:00 - 09:35 Dieter Jaksch
Dipole-dipole bound Rydberg molecules

09:35 - 10:05 Peter Schmelcher
Ultralong-Range Molecules in External Electric and Magnetic Fields

10:05 - 10:35 Johannes Deiglmayr
Rydberg macrodimers with a twist

10:35 - 11:10 Coffee break

11:10 - 11:40 Timothy Softley
Interaction of Rydberg hydrogen atoms and molecules with metallic, semiconductor and nanostructured surfaces

11:40 - 12:15 Kenji Ohmori
Ultrafast many-body dynamics in an ultracold Rydberg gas

12:15 - 12:45 Donatella Ciampini
Excitation dynamics and full counting statistics for resonant and off-resonant excitation of a strongly correlated cold Rydberg gas

13:00 - 16:00 Lunch & Posters

16:00 - 16:30 Silvia Bergamini
Computation and metrology with cold atoms in mixed states

16:30 - 17:00 Benoit Vermersch
Angular properties of vdW interactions with P and D Rydberg states: new features of the Rydberg Blockade phenomenon

17:00 - 17:30 Coffee break

17:00 - 19:00 Posters

20:30 - Conference dinner at the Hotel AC Santa Paula

Friday, September 12th

09:00 - 09:35 Alex Kuzmich
Quantum optics with Rydberg atoms

09:35 - 10:05 Alexei Ourjoumtsev
Quantum optics with an intracavity Rydberg gas

10:05 - 10:35 Robert Spreeuw
Magnetic microtrap lattices

10:35 - 11:10 Coffee break

11:10 - 11:45 Iacopo Carusotto
Quantum Fluids of Light

11:45 - 12:15 Fabio Mezzacapo
Quantum and classical glasses of ultrasoft particles in two dimensions

12:15 - 12:45 Przemek Bienias
Scattering properties of strongly interacting Rydberg polaritons

13:00 - 16:00 Lunch

16:00 - 16:30 Igor Lesanovsky
Strongly interacting Rydberg gases out of equilibrium

16:30 - 17:05 Daw-Wei Wang
Quantum phase transitions of Rydberg-dressed Fermi gases

17:05 - 17:40 Coffee break

IDEA FACTORY

How to transfer concepts from R&D into marketing and advertising

*Patrick Leisching**

TOPTICA Photonics AG

(*) Patrick.Leisching@toptica.com

This talk will introduce the basic concepts of a go-to-market strategy based on the tooling/concept of the "four P's of marketing". Based on the idea factory workshop from last summer in Pisa, we will select certain R&D or business ideas and develop a got-to-market strategy.

References

[1] http://de.slideshare.net/santoshtalkit/philip-kotler-marketing-11802729

Writing for different audiences: Colleagues, grants and the general public

*Oliver Morsch**

INO-CNR and Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy

(*) morsch@df.unipi.it

Writing is an essential part of a scientist's job, and writing well is a skill that needs time and practice to develop. In this series of three lectures we will look first at some general tools, such as how to structure a paper and tell a compelling story, how to write intelligibly, and how to revise a paper efficiently. After that, we will focus on different audiences and how to adapt the structure and style of our writing to those audiences and their expectations. In particular, we will look at strategies for explaining complex ideas in simple ways in order to communicate our research to the general public. Finally, we will do a few exercises that illustrate the concepts covered in the lectures.

INVITED TALKS

Strontium Ultracold Rydberg Gases

T. C. Killian*, F. B. Dunning, B. J. DeSalvo, J. A. Aman, P. McQuillen, X. Zhang, T. Strickler, and T. Langin

Rice University, Department of Physics and Astronomy, Houston, Texas, USA 77251

(*) killian@rice.edu

Alkaline-earth metal atoms are attracting increased attention for studies of ultracold Rydberg gases because of new opportunities created by strong core transitions accessible with visible light and the presence of excited triplet states. Core transitions can be used for flexible optical trapping and optical imaging of Rydberg atoms, and triplet levels appear promising for creating stronger optical coupling of ground and Rydberg levels with reduced light scattering. Compared to an alkali metal atom, the existence of both singlet and triplet Rydberg levels creates additional choices of configurations of excited states and associated Rydberg-Rydberg interactions.

I will describe recent experiments conducted at Rice University in which we take advantage of these opportunities with ultracold strontium gases. We have used imaging of core transitions to study the evolution of a dense Rydberg gas of $5sns\,{}^1S_0$ or $5snd\,{}^1D_2$ atoms to an ultracold neutral plasma [1]. We have also detected ultra-long-range Rydberg molecules formed from a $5sns\,{}^3S_1$ Rydberg atom and ground state atoms. Measurement of the binding energies of molecular states enable the determination of the s-wave scattering length in strontium for collisions between electrons and ground state atoms. This is a first step towards experiments with Rydberg dressing in quantum degenerate strontium gases.

References

[1] "Imaging the Evolution of an Ultracold Strontium Rydberg Gas," P. McQuillen, X. Zhang, T. Strickler, F. B. Dunning, and T. C. Killian, Phys. Rev. A **87**, 013407 (2013).

Rydberg blockade and dressing with Group II atoms

M. P. A. Jones, D. Boddy, D. P. Sadler, G. Lochead, A. D. Bounds, C. S. Adams, E. M. Bridge*

Joint Quantum Centre Durham-Newcastle (Durham University)

(*)m.p.a.jones@durham.ac.uk

We describe new perspectives for Rydberg physics provided by divalent atoms such as strontium. We will present recent results on the first observation of Rydberg blockade in a divalent system using a Coherent Population Trapping excitation scheme [1], where the second electron is used for Rydberg detection via autoionization. In addition, narrow intercombination lines enable two-photon excitation to the Rydberg state with low decoherence, providing an ideal system to investigate "Rydberg dressing". With the MPIPKS Dresden we have shown that applying this dressed interaction to strontium lattice clocks can also lead to the generation of significant squeezing that could be used to improve the signal-to-noise ratio [2]. We will present our progress towards intercombination line Rydberg dressing in our laboratory.

References

[1] G. Lochead *et al.*, Phys. Rev. A **87** 053409 (2013).

[2] L. I. R. Gil *et al.*, Phys. Rev. Lett. **112** 068103 (2013).

A Frequency Comb for Absolute Optical Frequency Measurement

*Russell Kliese**

TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Gräfelfing, Germany

(*) Russell.Kliese@toptica.com

Frequency combs provide the "clockwork" to relate optical frequencies to radio frequencies. Optical frequencies can be measured with an accuracy limited only by the radio frequency signal reference. In order to provide a stable link between the radio and optical frequencies, two parameters of the frequency comb must be fixed: the carrier envelope offset frequency and the pulse repetition-rate. We have developed an optical frequency comb that uses a difference frequency generation technique to stabilise the carrier envelope offset frequency. We have also evaluated a range of repetition-rate stabilisation methods. In this talk we discuss the frequency comb design, characterization, and optical frequency measurement.

Towards Hybrid Cavity Quantum Electrodynamics with Atoms and Circuits

Andreas Wallraff

ETH Zurich

www.qudev.ethz.ch, andreas.wallraff@phys.ethz.ch

In our lab we investigate the strong coherent interaction of light and matter on the level of individual photons and individual atoms or atom-like systems. In particular, we explore large dipole moment superconducting artificial atoms and Rydberg atoms interacting with radiation fields localized in quasi-one-dimensional coplanar or three-dimensional microwave frequency resonators. In one-dimensional resonators individual photons generate field strengths that exceed those of conventional mirror based resonators by orders of magnitude. This allows us to reach the strong coupling limit of cavity quantum electrodynamics (QED) using superconducting electronic circuits in an approach known as circuit QED. Since a number of years we develop an interface between circuit and atom based realizations of cavity QED. In particular, we explore the coupling of Rydberg atoms to on-chip and three-dimensional resonators which also allow for coupling to superconducting qubits. We investigate the interaction of ensembles of Helium Rydberg atoms created in a pulsed supersonic beam with microwave coherent fields above normal, superconducting and also dielectric surfaces in dependence on geometry and temperature. The microwave fields are either applied globally through a horn antenna or using an on-chip coplanar transmission line. We perform both steady-state spectroscopic and time-resolved coherent dynamics measurements of Rydberg atoms in the vicinity of surfaces [1, 2]. We detect the state of the Rydberg atoms using field ionization and develop novel schemes based on dispersive interaction with a resonator field. Our Rydberg atom experiments are performed in a cryostat between room temperature and 3 K [2] and are planned to be extended down to the millikelvin range. Ultimately, we plan to trap Rydberg atoms on-chip to investigate the single atom and single photon limit of cavity QED at the interface with superconducting circuits. This will allow us to explore a quantum coherent interface between atomic and solid state qubits in the context of quantum science and technology.

References

[1] S. Hogan et al., Phys. Rev. Lett. **108**, 063004 (2012)

[2] T. Thiele et al., Phys. Rev. A **90**, 013414 (2014)

From Rydberg switches to single-photon transistors

Gerhard Rempe

Max-Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany

gerhard.rempe@mpq.mpg.de

Present-day information processing employs, on short distances, electronic devices and, on long distances, photonic devices. Efficient interfaces are rare, so that all-optical information processing is appealing. Classical light switches and transistors have been studied decades ago, but only for high intensities owing to the small optical nonlinearities which were available. We now perform experiments in the quantum regime by exploiting the giant optical nonlinearity provided by the Rydberg blockade mechanism. Specifically, an incoming gate light pulse containing only one photon on average is stored as a Rydberg excitation in an ultracold atomic gas using electromagnetically induced transparency. Blockade then suppresses the transmission of the subsequent target pulse. The stored gate photon can be retrieved afterwards, signaling successful storage with an extinction factor of 20 for the target light [1]. Recent improvements made it possible to observe gain of 20, thus realizing a single-photon transistor [2]. Such device offers interesting perspectives in quantum communication and quantum information processing.

References

[1] S. Baur, D. Tiarks, G. Rempe, and S. Dürr, Phys. Rev. Lett. **112**, 073901 (2014).

[2] D. Tiarks, S. Baur, K. Schneider, S. Dürr, and G. Rempe, Phys. Rev. Lett. **113**, (2014).

Rydberg mediated entanglement with trapped atoms

*Mark Saffman**

Department of Physics, University of Wisconsin, Madison, WI, 53706 USA

(*) msaffman@wisc.edu

We are exploring several different approaches towards entanglement mediated by Rydberg blockade interactions. I will present results on entanglement experiments with single Cs atoms performed in a 2D trap array[1] defined by blue detuned light. An alternative to single atom qubits is to work with small emsembles which can provide strong atom-light coupling. We have demonstrated $|W\rangle$ state preparation[2], and will present measurements of the coherence time and blockade physics with Rb atom ensembles. These results set the groundwork for entanglement of multi-atom ensemble qubits. Finally, we are investigating the use of rare earth atoms with large ground state hyperfine manifolds for collective encoding of qubit registers. We have performed Rydberg spectroscopy of cold Ho atoms in a MOT[3] and identify ns and nd Rydberg series which we plan to use for blockade measurements.

Work supported by IARPA, ARO, AFOSR, and NSF.

References

[1] M. J. Piotrowicz, M. Lichtman, K. Maller, G. Li, S. Zhang, L. Isenhower, and M. Saffman, *Two-dimensional lattice of blue-detuned atom traps using a projected Gaussian beam array*, Phys. Rev. A, **88**, 013420 (2013).

[2] M. Ebert, A. Gill, M. Gibbons, X. Zhang, M. Saffman, and T. G. Walker, *Atomic Fock State Preparation Using Rydberg Blockade*, Phys. Rev. Lett., **112**, 043602 (2014).

[3] J. Miao, J. Hostetter, G. Stratis, and M. Saffman, *Magneto-optical trapping of Holmium atoms*, Phys. Rev. A, **89**, 041401(R) (2014).

Measuring dipole-dipole interactions between two single Rydberg atoms

T. Lahaye, S. Ravets, H. Labuhn, D. Barredo, L. Béguin, and A. Browaeys*

Laboratoire Charles Fabry, Institut d'Optique, CNRS, Palaiseau, France

(*) thierry.lahaye@insititutoptique.fr

I will report on our measurements of dipole-dipole interactions between Rydberg states using single atoms held in SLM-generated arrays of optical microtraps [1]. With two single atoms, we have measured the dependence on distance [2] and angle [3] of the van der Waals interactions between atoms prepared in $|nD_{3/2}\rangle$ states (with n in the range 50–80). Using an electrically tuned Förster resonance, we have also studied the *resonant* dipole-dipole interaction, and directly observed the coherent oscillation between the degenerate pair states $|59D_{3/2}, 59D_{3/2}\rangle$ and $|61P_{1/2}, 57F_{5/2}\rangle$ with a frequency scaling as the inverse third power of the distance between the atoms [4]. Finally I will describe our progress towards experiments with a larger number of atoms, with, as a first experimental result, the observation of strong Rydberg blockade for $N = 3$ atoms [3].

References

[1] F. Nogrette *et al.*, Phys. Rev. X **4**, 021034 (2014).

[2] L. Béguin *et al.*, Phys. Rev. Lett. **110**, 263201 (2013).

[3] D. Barredo *et al.*, Phys. Rev. Lett. **112**, 183002 (2014).

[4] S. Ravets *et al.*, arXiv:1405.7804.

Few-body interactions control in cold Rydberg atoms

P. Cheinet, R. Faoro, B. Pelle, A. Zuliani, E. Arimondo and P. Pillet*

Laboratoire Aimé Cotton, Orsay, France

(*) patrick.cheinet@u-psud.fr

Previously in Laboratoire Aimé Cotton, we have succeeded to isolate a 4-body interaction process [1] appearing as a specific resonance of energy exchange between 4 Rydberg atoms. This process originated from the coincident recombination of two 2-body energy exchange resonances [2] called Förster resonance in analogy to FRET in biomolecules:

$$2 \times np_{3/2} \leftrightarrow ns + (n+1)s \quad (1)$$
$$2 \times (n+1)s \leftrightarrow np_{1/2} + nd_{5/2} \quad (2)$$

Such a coincidence prevents *a priori* to extend this 4-body process to other systems, atoms or molecules. We have thus searched for more general processes. We will present here a new resonant 3-body energy transfer process observed in cesium Rydberg atoms:

$$3 \times np_{3/2}m \leftrightarrow ns + (n+1)s + np_{3/2}m' \quad (3)$$

This process is a revival of the 2-body resonance presented in (1), induced by the much smaller energy exchange of a third atom changing only its magnetic sub-level. We have found that this exchange process is particularly strong as presented in Fig 1 for the $32p_{3/2}m_{1/2}$ state. It is also generalisable to any atom or molecule presenting a Förster resonance from a state with $J > 1/2$. This new FRET process could be used to design a 3-Qbit quantum gate like the (Fredkin) CSWAP-gate, or to provide heralded entanglement between 2 atoms, measuring the 3^{rd}. This type of few-body FRET is also likely to participate in light harvesting complexes and its better understanding could help improving new solar cell technology which already tries to mimic light-harvesting.

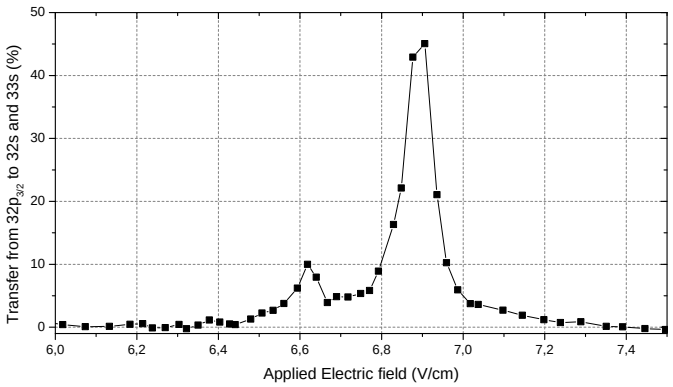

Figure 1: Resonant exchange from $32p_{3/2}m_{1/2}$ to $32s + 33s$. The 2-body resonance is expected at 6.89V/cm while the 3-body resonance is calculated at 6.61V/cm.

References

[1] J. H. Gurian *et al.* PRL **108** 023005 (2012)

[2] K. A. Safinya *et al.* PRL **47** 405 (1981)

Simulating dipolar energy transport with giant atoms

Hanna Schempp, Vladislav Gavryusev, Miguel Ferreira Cao, Georg Günter, Shannon Whitlock, Matthias Weidemüller*

Physicalisches Institut, Universität Heidelberg, Germany

(*) whitlock@physi.uni-heidelberg.de

Energy transport is an important theme in natural processes, e.g., chemical reactions and photosynthesis. There is ongoing debate on how the environment influences the efficiency of energy transfer in these systems and to which extent quantum mechanics plays a role. By interfacing electronically highly excited (Rydberg) atoms with laser light we simulate energy transfer dynamics in a controlled many-body system. In particular, Rydberg atoms experience quantum state changing interactions similar to Frster processes in complex molecules, offering a model system to study the nature of dipole-mediated energy transport. The extension to multiple interacting excitations could enable elementary realisations of quantum spin models involving strong and long-range spin-dependent interactions. We report on a new imaging method, which we apply to monitor the migration of electronic excitations with high time and spatial resolution using a background atomic gas as an amplifier. Through precise control of interactions and the coupling to the environment via the laser fields, we find different mechanisms at work which shed new light on the nature of energy and spin transport in complex quantum systems.

References

[1] *Observing the Dynamics of Dipole-Mediated Energy Transport by Interaction-Enhanced Imaging*, G. Günter, H. Schempp, M. Robert-de-Saint-Vincent, V. Gavryusev, S. Helmrich, C.S. Hofmann, S. Whitlock and M. Weidemüller, Science 342, 954-956 (2013)

Towards quantum simulations of chemical and biological processes using ultra-cold Rydberg atoms

*Sebastian Wuester **

Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

(*) sew654@pks.mpg.de

In the envisioned implementations of quantum gates using Rydberg atoms, residual atomic motion is usually an unavoidable perturbation and source of noise. In contrast for quantum transport phenomena in chemical and biological processes, motion can be beneficial.

During acceleration of several Rydberg atoms due to resonant dipole-dipole interactions, the responsible Born-Oppenheimer surfaces of the atomic system provide an intricate link between atomic motion and excitation transport. Conical intersections among these dipole Born-Oppenheimer surfaces would provide experimental access to many-body dynamics near an intersection and can further be functionalised as switches for exciton transport.

On shorter time scales where motion is no longer crucial, the system shows parallels to energy transport in light harvesting complexes. Consequently Rydberg atoms can provide a clean analog system for the quantum simulation of photosynthetic energy transport, into which crucial complex features like disorder and decoherence can be introduced in a controlled manner. This control can be achieved by embedding the assembly of Rydberg atoms into a background atomic gas.

Dipole-dipole bound Rydberg molecules

Martin Kiffner, Wenhui Li, and *Dieter Jaksch**

Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom and Centre for Quantum Technologies, National University of Singapore

* Dieter.Jaksch@physics.ox.ac.uk

In the first part of my talk I will discuss the physics of two [1, 2, 3] and three [3, 4] ultracold Rydberg atoms interacting via the dipole-dipole interaction. These systems can form micrometer sized dimer molecules whose relative dynamics is governed by artificial gauge fields. In particular I will show that these fields exhibit magnetic monopoles and give rise to synthetic spin-orbit coupling. Furthermore, I will discuss three atom bound states that do not have a two atom equivalent. The binding mechanism leading to these states is substantially different from Efimov physics. I will also show how these molecular states can be engineered in the laboratory and how the exaggerated properties of Rydberg atoms make their features directly observable using current experimental technology. In the second part of my talk I will discuss the prospect of forming strongly correlated electron gases [5] starting from ultracold Rydberg atoms in optical lattices. I will describe our progress in electronic structure calculations for Rydberg atoms with electrons that are delocalized over the optical lattice. I will explain how this system might form a Rydberg crystal with strongly correlated electrons, a spatial periodicity of several hundred nanometers, and coherent dynamics on experimentally resolvable picosecond time scales. I will present the exciting properties that such an electronic system might possess and discuss some of the major challenges in realizing them.

References

[1] M. Kiffner, W. Li and D. Jaksch, Magnetic Monopoles and Synthetic Spin-Orbit Coupling in Rydberg Macrodimers, Phys. Rev. Lett. **110**, 170402 (2013).

[2] M. Kiffner, W. Li and D. Jaksch, Abelian and non-Abelian gauge fields in dipole-dipole interacting Rydberg atoms, J. Phys. B: At. Mol. Opt. Phys. **46**, 134008 (2013).

[3] M. Kiffner, M. Huo, W. Li and D. Jaksch, Few-body bound states of dipole-dipole-interacting Rydberg atoms, Phys. Rev. A **89**, 052717 (2014).

[4] M. Kiffner, W. Li and D. Jaksch, Three-Body Bound States in Dipole-Dipole Interacting Rydberg Atoms, Phys. Rev. Lett. **111**, 233003 (2013).

[5] M. Kiffner, D. Ceresoli, W. Li and D. Jaksch, Electronic structure of excited valence electrons of ultracold atoms in a Mott insulating state, preprint

Ultralong-Range Molecules in External Electric and Magnetic Fields

Peter Schmelcher and Markus Kurz

Centre for Optical Quantum Technologies

University of Hamburg

Luruper Chaussee 149

22761 Hamburg, Germany

(*) pschmelc@physnet.uni-hamburg.de

We investigate the structure of ultralong-range Rydberg molecules in external electric and magnetic fields. After summarizing the response of ultralong-range Rydberg molecules to pure electric and pure magnetic fields, we address the situation of combined electric and magnetic fields for the parallel and perpendicular configurations. We take into account both the s-wave and p-wave interactions of the Rydberg electron and the neutral ground state atom. The strong impact of the p-wave interaction on the ultralong-range molecular states is demonstrated. In the presence of external fields the angular degrees of freedom acquire vibrational character and we encounter two- and three-dimensional oscillatory adiabatic potential energy surfaces for the parallel and crossed field configuration, respectively. The equilibrium configurations of local potential wells can be controlled via the external field parameters for both field configurations depending of the specific degree of electronic excitation. This allows to tune the molecular alignment and orientation. The resulting electric dipole moment is in the order of several kDebye and the rovibrational level spacings are in the range of $2 - 250$ MHz. Both properties are analyzed with of varying field strengths.

References

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Rydberg macrodimers with a twist

Johannes Deiglmayr, Heiner Saßmannshausen, and Frédéric Merkt*

ETH Zürich, Laboratory of Physical Chemistry, Vladimir-Prelog-Weg 2, CH-8093 Zürich, Switzerland
(*) j.deiglmayr@phys.chem.ethz.ch

The excitation of ultracold atoms to interacting Rydberg states has given rise to the observation of a wide range of fundamental phenomena such as the formation of ultracold neutral plasmas, the conditional blockade of excitation, and the formation of macrodimers. In a macrodimer, two atoms are bound by long-range dispersion forces between the highly excited Rydberg states [1].

Here we report the direct excitation of pairs of cesium atoms from the ground state to molecular states correlating asymptotically to $n_s s$-$n_f f$ asymptotes by transform limited UV laser pulses (linewidth 140 MHz). These pair resonances are interpreted as originating from the dipole-quadrupole interaction between the $n_s s$-$n_f f$ pair states and close-by np-np asymptotes ($22 \leq n \leq 32$) and have not been observed before. Our interpretation is supported by Stark spectroscopy of the pair states and a detailed modeling of the interaction potentials. We argue that the dipole-quadrupole interaction does conserve neither the electronic parity $\pm$ nor the g/u symmetry, both of which are commonly associated with homonuclear dimers. Because the total parity of the interacting system (which can be obtained as a product of the parities of the electronic and rotational wave functions) has to be conserved, the excitation of sf-pair resonances implies an entanglement of the parities of the eletronic and the rotational wave function. This non-Born-Oppenheimer coupling is facilitated by the near-degeneracy of even and odd L partial waves in the atom-atom scattering which have opposite parity.

The setup [2] and experimental results will be presented and further implications of our findings will be discussed.

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Interaction of Rydberg hydrogen atoms and molecules with metallic, semiconductor and nanostructured surfaces

*Timothy P Softley**, Mark S. Ford, Eric So, Sashikesh Ganeshalingam, Jemma Gibbard, Mark Dethlefsen and Mike Kohlhoff

Department of Chemistry, University of Oxford, Chemistry Research Laboratory, Mansfield Rd, Oxford, United Kingdom

(*) tim.softley@chem.ox.ac.uk

We describe experiments and theory in which a beam of H atoms or H_2 molecules is incident on a solid surface leading to charge transfer of the Rydberg electron to the surface [1]. The process is monitored by pulling the ions that are formed away from the surface to a detector. By varying the extraction field or the velocity of the incidents atoms or molecules, information can be extracted about the probability of ionization at a given distance from the surface. The probability depends on the quantum numbers of the Rydberg species that are populated in the laser excitation and also on the complex map of energy levels and their crossings in the presence of changing fields as the surface is approached. More importantly it also depends on the electronic and geometrical structure of the surface, and on the charge distribution in the surface where appropriate. In this talk, results will be presented for a range of different surface types including, semiconductor silicon surfaces with varying dopant concentrations [2, 3], copper surfaces with a projected band gap at the surface, and nanostructured surfaces with gold nanoparticles deposited on a silicon wafer.

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Ultrafast many-body dynamics in an ultracold Rydberg gas

Nobuyuki Takei[1,2,3], *Christian Sommer*[1,2,3], *Claudiu Genes*[3,4], *Guido Pupillo*[3,5], *Haruka Goto*[1], *Kuniaki Koyasu*[1,2,3], *Hisashi Chiba*[1,3,6], *Matthias Weidemüller*[3,7], *and 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] Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria,
[5] IPCMS (UMR 7504) and ISIS (UMR 7006), University of Strasbourg and CNRS, 67000 Strasbourg, France,
[6] Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan,
[7] Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

(*) ohmori@ims.ac.jp

Many-body interactions govern a variety of important physical phenomena such as the emergence of magnetism and superconductivity in condensed matter. Understanding those interactions beyond mean field is one of the holy grails of modern physics. Atomic, molecular, and optical physics with advanced laser technologies has recently emerged as a new platform to study many-body systems, due to the development of a toolbox for coherent manipulation of the interactions and consequent engineering of model Hamiltonians. One of its latest developments is the study of long-range interactions among ultracold particles such as atoms in an optical lattice clock [1], polar molecules [2], magnetic atoms [3], ions [4], and Rydberg atoms [5]. Advantages of Rydberg atoms over the other systems include their large dipole moments and excellent tunability of interactions, which can be switched on and off actively. Most of the relevant Rydberg experiments have so far been performed with narrow-band lasers in a regime referred to as "Rydberg blockade", in which only one Rydberg atom can exist in a sphere whose radius is typically on the order of several microns. Recent breakthrough experiments in this blockade regime have shown the first examples of correlated many-body states of Rydberg atoms [5]. Here we demonstrate a new strategy to realize a Rydberg gas in a complementary regime, in which we have circumvented the Rydberg blockade with a broadband picosecond (ps) laser pulse to increase the interaction by several orders of magnitude. The property of this strongly interacting Rydberg gas has been investigated by time-domain Ramsey interferometry with attosecond precision. Our ps laser pulse allows for real-time observation of coherent and ultrafast many-body dynamics manifested in Ramsey oscillations modulated on the ps timescale. We have found that this ultrafast modulation arises from the collective interaction among several tens of Rydberg atoms. Our new approach opens a new avenue to observe and manipulate the highly nonequilibrium dynamics of strongly interacting many-body systems on the ultrafast timescale.

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Excitation dynamics and full counting statistics for resonant and off-resonant excitation of a strongly correlated cold Rydberg gas

Donatella Ciampini

Dipartimento di Fisica "E.Fermi", INO-CNR and CNISM UdR Pisa, L.go B. Pontecorvo 3, 56127 Pisa, Italy

ciampini@df.unipi.it

Atoms in high-lying Rydberg states strongly interact with each other via the dipole-dipole or van-der-Waals potential thus permitting the exploration of a wide range of many-body phenomena in strongly interacting systems. The strong interactions between Rydberg atoms under resonant laser driving and non-dissipative conditions become manifest either as spatial correlations compatible with a radius of blockade around an excited atom or through a reduction of fluctuations leading to sub-Poissonian statistics [1]. On the other hand, recent publications show how dissipation leads to novel phases [2, 3] and may facilitate the creation of pure and coherent many-body states.

I will present experimental observations for both the resonant and the off-resonant excitation scheme, with the excitation laser having a finite detuning from the $^{87}Rb\ 70S$ state. In such an off-resonant excitation scheme, the detuning can compensate for the energy shift induced by the Rydberg-Rydberg interaction, giving rise to resonant interaction channels [4, 5]. A pair of atoms undergoes a pair excitation if the atomic interaction matches the laser energy defect/excess. After such event, neighbouring ground-state atoms at the resonant distance have an enhanced excitation probability, owing to the interaction induced energy shifts. As a consequence an already excited Rydberg atom pair (or a Rydberg atom, off-resonantly excited) can shift other atoms into resonance, in a domino effect, leading to an increasing overall Rydberg excitation probability. The histograms of these distributions become strongly bimodal for long excitation time values, pointing out that dissipation favors the appearance of bimodality. I will illustrate the off-resonant excitation dynamics and full counting statistics in experiments in which the growth of excitations is controlled by using an initial Rydberg excitation as a seed. The information extracted from the complete characterization of the full counting distribution makes possible a direct comparison with theoretical predictions that is far more sensitive than, i.e., the mean and standard deviation alone.

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Computation and metrology with cold atoms in mixed states

*Chris Mansell, Katarzyna Kryzanowska, Calum MacCormick, Silvia Bergamini**

Department of Physical Sciences, The Open University, Milton Keynes, United Kingdom

(*) s.bergamini@open.ac.uk

The use of Rydberg interactions and ensembles of cold atoms in mixed state for the implementation of a protocol for deterministic quantum computation with one quantum bit (DQC1 [1]) is discussed. This protocol relies on one pure control qubit together with a register of completely-mixed qubits. DQC1 is a non-universal model that can speed up some computational tasks for which no efficient classical algorithms are known. Whilst requiring only a single qubit with coherence, for these specific tasks, its power scales up with the number of qubits in a mixed state. Although it has been shown that this scheme contains little to no entanglement, non-classical correlations are present in the output state of the DQC1 which can be quantified in terms of quantum discord. To date, successful experiments based on DQC1 have evaluated the normalised trace of a two-by-two unitary matrix [2] and performed the approximation to the Jones polynomial with a system of four qubits, thus demonstrating the ground principle of mixed state computation.

An experimental test for the true scalability of the protocol based on cold atoms and Ryderg interactions and to study the physics of discord is proposed, as well as the possibility of extending to non-trivial problems [3], such as many-body physics.

A further scheme is presented, derived from the DQC1 model, that enables quantum phase estimation and promises high-precision measurement, without relying on quantum entanglement and only using discord in the probe states [4]. Modelling of this scheme, using cold atoms in dipole traps, demonstrates that the register of partly mixed qubits becomes a powerful resource for phase estimation when supplied with the coherence from the control qubit.

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Angular properties of vdW interactions with P and D Rydberg states: new features of the Rydberg Blockade phenomenon

Benoit Vermersch, Alexander Glaetlze, Matthias Punk and Peter Zoller*

Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria
Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria

(*) benoit.vermersch@uibk.ac.at

The Rydberg Blockade mechanism relies on the assumption that the dynamics of the atoms can be described by simple two-level systems made of a ground and a Rydberg state. However in the van der Waals (vdW) regime where interactions scale as $1/r^6$, magnetic levels are in general coupled leading to a mixing between the different Rydberg states of the fine structure [1]. This coupling is negligible concerning $S_{1/2}$ states but is the same order of magnitude as the interaction energy for P or D states. It is therefore crucial to study its influence on the Rydberg blockade.

The effect of the vdW coupling can be tuned by two parameters: the angle θ between the atoms and the quantization axis which controls the vdW interactions and a magnetic field which energetically separates the Zeeman levels. We studied the key influence of these two parameters in a typical Rydberg blockade setup and showed in particular the existence of so-called "magic distances" at which the competition between the laser, the interactions and the magnetic field leads to the generation of entangled doubly excited states.

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QUANTUM OPTICS WITH RYDBERG ATOMS

*Alex Kuzmich**

Department of Physics, University of Michigan, Ann Arbor, MI 48109

(*) akuzmich@umich.edu

Ultra-cold atomic gases can be driven into a Rydberg level in a regime dominated by many-body effects. Single photons can be generated deterministically, and entangled with atomic excitations, by exploiting the strong interactions of atoms excited into Rydberg levels of principal quantum number $n \sim 100$. Rydberg-level interactions lead to two distinct mechanisms, the spin-wave dephasing and excitation blockade, contributing to the observed phenomena. Many-body Rabi oscillations seen in such ensembles hold promise for the simulation of complex quantum systems.

Quantum optics with an intracavity Rydberg gas

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

[1] Laboratoire Charles Fabry, Institut d'Optique, CNRS, Univ. Paris-Sud,
2 Avenue Fresnel, 91127 Palaiseau, France
[2] Laboratoire Aimé Cotton, CNRS, Univ. Paris-Sud, ENS-Cachan,
Bât. 505, Campus d'Orsay, 91405 Orsay, France

(*) alexei.ourjoumtsev@institutoptique.fr

Our project aims at creating strong dispersive interactions between optical photons using an interacting Rydberg gas trapped inside an optical cavity. After observing a dispersive non-linear response of the gas in the classical regime [1, 2], we have shown that our experimental system allowed us to create single heralded excitations in the atomic gas and efficiently extract them as single-mode free-propagating photons presenting strongly non-classical, negative Wigner functions [3, 4]. Our current theoretical and experimental efforts focus on reaching a regime where Rydberg interactions are strong enough to create such non-classical states deterministically [5, 6].

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MAGNETIC MICROTRAP LATTICES

*Robert Spreeuw**

Van der Waals-Zeeman Institute, Univ. of Amsterdam, the Netherlands

(*) r.j.c.spreeuw@uva.nl

We investigate lattices of magnetic microtraps holding mesoscopic clouds of ultracold ^{87}Rb atoms as a platform for the study of strongly interacting Rydberg atoms.

At the heart of our experiment is an atom chip made out of permanently magnetised film, lithographically patterned to create a two-dimensional lattice of Ioffe-Pritchard type magnetic traps [1]. Excitation of Rydberg atoms in these tight magnetic traps takes us into a very interesting regime, confining ensembles of atoms to a volume comparable to a typical Rydberg orbit. Strong dipole blockade is thus expected, and the strong magnetic field gradient will strongly distort the Rydberg wavefunction. The Rydberg atoms will also be excited only few μm from a metal surface and will interact with their mirror image.

Our atom chip contains lattices with square as well as hexagonal symmetries, both with a $10\,\mu$m lattice parameter [2]. We populate a few hundred microtraps, each holding an ensemble of about a hundred ultracold rubidium atoms. Quantum information can be stored in these ensembles as superpositions of collective hyperfine states. Switchable interaction will be enacted by transient excitation or dressing to Rydberg levels.

In addition we are developing lattices with lattice parameter in the 100 nm range. This should yield an implementation of the Hubbard model in novel parameter regimes, with strongly increased energy scales compared to current optical lattices.

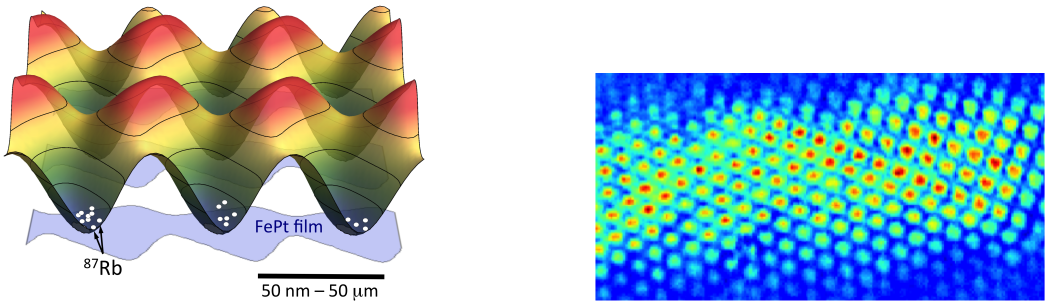

Figure 1: Left: patterned, magnetised film (blue) with the calculated magnetic potential landscape. Right: absorption image of joined square and triagonal lattices of microtraps for Rydberg experiments, with $10\,\mu$m lattice period.

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Quantum Fluids of Light

*Iacopo Carusotto**

INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, I-38123 Povo, Italy

(*) carusott@science.unitn.it

A few years after the first observation of Bose-Einstein condensation, quantum gases of dressed photons in semiconductor microcavities (the so-called exciton-polaritons) are a powerful workbench for the study of phase transitions and many-body effects in a novel non-equilibrium context [1].

In this talk, I will first briefly review remarkable experiments investigating superfluid hydrodynamics effects in photon fluids hitting localized defects: depending on the flow speed, a wide range of behaviors have been observed, from superfluid flow, to the super-sonic Mach cone, to the nucleation of topological excitations such as solitons and vortices.
I will then illustrate recent theoretical studies in the direction of generating strongly correlated photon gases, from Tonks-Girardeau gases of impenetrable photons in one-dimension, to quantum Hall liquids in the presence of artificial magnetic fields.
Advantages and disadvantages of the different material platforms in view of generating and detecting strongly correlated gases will be reviewed, in particular laterally patterned microcavity and micropillar devices in the optical range, gases of Rydberg atoms, and circuit-QED devices in the microwave domain.

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Quantum and classical glasses of ultrasoft particles in two dimensions

*Fabio Mezzacapo**

PCMS (UMR 7504) and ISIS (UMR 7006), Université de Strasbourg and CNRS, Strasbourg, France

(*) mezzacapo@unistra.fr

We study the classical and quantum phases of monodisperse particles interacting via soft-core potentials in two spatial dimensions. Using a combination of exact theoretical methods, we demonstrate that a glass phase intervenes between the classical solid ground-state and a high-temperature liquid phase, in a wide range of parameters. Quantum fluctuations in the semi-classical regime are found to destabilize the glass into a liquid phase. Bosonic quantum statistics can have the opposite effect of stabilizing a solid-type phase.

Scattering properties of strongly interacting Rydberg polaritons

Przemek Bienias

University of Stuttgart, Germany

(*) przemek@theo3.physik.uni-stuttgart.de

Recently, the combination of slow light polaritons with the strong interactions between Rydberg atoms has emerged as a promising system for inducing a strong interaction between photons [1, 2]. Potential applications range from the implementation of phase gates for photons, to single photon sources, as well as the generation of strongly correlated states of photons. In this talk, we present a theoretical framework describing slow-light polaritons interacting via atomic Rydberg states [3]. The method allows us to analytically derive the scattering properties of two polaritons. We identify new parameter regimes where polariton-polariton interactions are repulsive. Furthermore, in the regime of attractive interactions, we identify multiple two-polariton bound states, calculate their dispersion, and study the resulting scattering resonances. Finally, we discuss the implications of our results to the ongoing experiments and to the effective many body theory for strongly interacting Rydberg polaritons.

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Strongly interacting Rydberg gases out of equilibrium

*Igor Lesanovsky**

School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

(*) igor.lesanovsky@nottingham.ac.uk

In this talk I will focus on the non-equilibrium dynamics of strongly interacting Rydberg gases. Here non-trivial behaviour is generated by the competition between coherent laser excitation, dissipation and the interaction. In the limit of strong dissipation the dynamics is hierarchical and correlated. Here it is possible to establish a connection to soft condensed matter systems such as kinetically constrained spin ensembles that are used as models for glassy dynamics [1]. Moreover, the Rydberg system features other types of strongly correlated soft-matter type behaviour such as facilitation, nucleation and growth [2].

Beyond that I will discuss a dynamical transition between two stationary states characterized by different excitation densities that has recently observed experimentally [3]. The structure and properties of the phase diagram of the Rydberg gas are determined and the universality class of the transition, both for the statics and the dynamics, is identified. It turns out that the proper dynamical order parameter is in fact not the excitation density and that evidence suggests that the dynamical transition is in the "model A" universality class [4]. This means it features a non-trivial Z_2 symmetry and a dynamics with non-conserved order parameter.

This perspective permits a quantitative understanding of a recent experiment [3] which observed bistable behaviour as well as power-law scaling of the relaxation time. The latter emerges not due to critical slowing down in the vicinity of a second order transition, but from the non-equilibrium dynamics near a so-called spinodal line.

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Quantum phase transitions of Rydberg-dressed Fermi gases

Daw-Wei Wang

Department of Physics, National Tsing Hua University, Hsinchu, Taiwan 300, ROC
Institute of Physics, National Center for Theoretical Science, Hsingchu, Taiwan 300, ROC

(*) dwwang@phys.nthu.edu.tw

We theoretical investigate the quantum phase diagrams of a single component Fermi gas, which is weakly coupled to a Rydberg state by a two photon transition. The effective interaction can be either repulsive or attractive with a finite soft core radius via blockade effect. For the attractive case, we systematically study the p-wave superfluidity, and obtain the quantum phase diagram of three different symmetries in the pairing wavefunction: polar, axial, and axi-planar phases [1]. The last one is shown to be stabilized by the finite ranged nature of the effective interaction. The transition temperature is estimated to be about 0.1EF in the current experimental regime of Li6. For the repulsive case, we calculate the collectivemode dispersion as well as the density-density correlation function [2]. We find a roton-like minimum in the collective mode and it becomes softened when the blockade radius is large enough, leading to an instability toward a charge-density wave order in a continuous space by breaking rotational and translation symmetries. We further compare it with the Pomeranchuk instability in condensed matter system and discuss the possible experimental parameter regime for these quantum phase transitions.

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POSTERS

Poster 1

Antiferromagnetic long-range order in dissipative Rydberg lattices

Wildan Abdussalam[1]*, *Michael Hönig* [2], *Michael Fleischhauer* [2], *Thomas Pohl* [1]

[1] Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden, Germany

[2] Fachbereich Physik und Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, D-67663 Kaiserslautern, Germany

(*) wildan@pks.mpg.de

We study the dynamics of dissipative spin lattices with power-law interactions, realized via few-level atoms driven by coherent laser-coupling and decoherence processes. Using Monte-Carlo simulations, we determine the phase diagram in the steady state and analyze the dynamics of its generation. As opposed to mean-field predictions and nearest-neighbour models there is no phase transition to long-range ordered phases for realistic interactions and resonant driving. However, for finite laser detunings, we demonstrate the emergence of crystalline order with a vanishing dissipative gap. Although the static and dynamical critical exponents of the revealed dissipative phase transition fall into the 2D Ising universality class the found steady states differ considerably from those of an equilibrium Ising magnet. Two complementary schemes for an experimental implementation with cold Rydberg atoms are discussed.

Poster 2

Impact of an external electric field in a triatomic Rydberg molecule

Javier Aguilera Fernández and Rosario González-Férez

Universidad de Granada, Spain

(*) aguilerajavier@ugr.es

A triatomic Rydberg molecule is formed from a Rydberg atom and two ground state atoms. Using first oder perturbation theory we derive the adiabatic energy surfaces of the molecular Rydberg states in the field-free case and in the presence of an external electric field. We consider the case when the two ground state atoms are placed on non-symmetric positions with respect to the Rydberg ion. We investigate the properties and structure of these systems in detail. We investigate the metamorphosis of the Born-Oppenheimer potential curves, essential for the binding of the trimer, with varying electric field strength.

Poster 3

LATTICE BOSONIC SYSTEMS WITH LONG–RANGE INTERACTIONS

*Adriano Angelone**

Université de Strasbourg, Strasbourg, France

(*) aangelone@unistra.fr

Studies on bosonic lattice systems with strong interactions have proven that systems of this kind show many different and interesting physical phenomena (for instance, see [1], where the simultaneous existence of Spin–Glass behaviour and Bose–Einstein condensation has been proven for such systems in the presence of geometrical frustration). Our focus is to extend these studies to other regimes and interactions, including long–range potentials. In order to study these systems we will use the Worm Quantum Monte Carlo algorithm, due to its flexibility and improvements over other methods.

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Poster 4

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

Malte Schlosser, Sascha Tichelmann, Daniel Ohl de Mello, Felix Stopp, Kathrin Luksch, *Gerhard Birkl**

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

(*) gerhard.birkl@physik.tu-darmstadt.de

Efficient quantum simulation and quantum information processing requires scalable architectures that guarantee the allocation of large-scale qubit resources as well as suitable methods for quantum gate implementations, such as Rydberg interactions based two-qubit gates for neutral atoms. In our work, we focus on the implementation of multi-site geometries based on microfabricated optical elements. This approach allows us to develop flexible, integrable, and scalable configurations of multi-site focused beam traps for the storage and manipulation of single-atom qubits and their interactions [1, 2].

We give an overview on the investigation of ^{85}Rb atoms in two-dimensional arrays of well over 200 individually addressable dipole traps featuring trap sizes and a tunable site-separation in the single micrometer regime. Furthermore, we experimentally demonstrate single-atom quantum registers with more than 100 occupied sites, single-site resolved addressing of single atom quantum states in a reconfigurable fashion [3] and discuss progress in introducing Rydberg based interactions in our setup.

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Poster 5

A strontium vapour cell with electrodes for spectroscopy, Rydberg atom detection and Stark maps

Alistair Bounds, Daniel Sadler, Danielle Boddy, Elizabeth Bridge, Charles Adams, Matthew Jones*

Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University, Durham, DH1 3LE, UK

(*) a.d.bounds@dur.ac.uk

Coherent excitation of cold atoms to Rydberg states provides a platform for quantum many-body systems. Ultracold Rydberg physics in strontium allows spatially resolved, state selective Rydberg atom detection [1][2], narrow intercombination lines and investigation of Rydberg dressing, which may lead to spin-squeezing in atomic lattice clocks [3] and supersolid states in Sr BEC [4].

We describe a dispenser based strontium vapour cell developed for laser spectroscopy, laser locking and measuring Stark maps of Rydberg states. Sr has negligible room temperature vapour pressure and reacts with glass, so cannot be used in a conventional vapour cell. The cell builds on previous work [5] and uses standard conflat vacuum pieces, operates at room temperature without a pump or buffer gas and uses a current activated dispenser to produce an atomic beam. A pair of electrodes and a Faraday cup inside the cell create a controllable uniform electric field and provide detection of ions and field ionisation of Rydberg atoms, allowing detection of Rydberg atoms through field- or auto-ionisation [2]. The cell has optical access to the atomic beam on one axis and observation of fluorescence through a stainless steel mesh electrode on an orthogonal axis. We present the cell design and preliminary results.

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Poster 6

Microwave control of the interaction between two optical photons

H. Busche, D. Paredes Barato, S. W. Ball, D. Maxwell, D. J. Szwer, P. Huillery, M. P. A. Jones, and C. S. Adams*

Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University, South Road, Durham, DH1 3LE, United Kingdom

(*) hannes.busche@durham.ac.uk

Photons are ideal carriers of quantum information, but the lack of interactions between them makes processing of the information difficult. We address this problem by storing photons as Rydberg polaritons in a cloud of optically trapped cold atoms, thus mapping the long ranged dipolar interactions between Rydberg excitations onto the light field. The resulting effective interaction at the single photon level can be controlled using microwave fields [1, 2].

Recently, a new experimental apparatus was built that will allow us to store single photons in individually addressable sites and operate at high repetition rates to achieve good photon statistics. In this new setup, we plan to explore applications of Rydberg nonlinear quantum optics, such as the implementation of a universal quantum gate for photonic qubits [3].

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Poster 7

Dynamics of strongly interacting photons in waveguides: a generalized input-output formalism

T. Caneva[1*], *M. Manzoni*[1], *T. Shi*[2], *J. I. Cirac*[2], *D. E. Chang*[1]

[1] ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain.

[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany.

(*) tommaso.caneva@icfo.es

We present a generalized input-output formalism to describe the propagation of strongly interacting photons through an atomic ensemble. Standard approaches typically involve approximations to eliminate the atomic degrees of freedom, to subsequently arrive at a nonlinear field equation describing the optical modes. On the contrary, we show that, by effectively integrating out the photonic field, a spin model containing only discrete atomic degrees of freedom can be obtained. Then by explicitly solving for the atomic dynamics, the optical fields are reconstructed exactly, including S-matrix and any correlation function. Our approach to provide a complete description of the system dynamics represents a powerful tool to explore a wide range of new phenomena in nonlinear quantum optics. We discuss the formalism in several experimental situations.

Poster 8

Deterministic entanglement of Rydberg ensembles by engineered dissipation

Durga B Rao Dasari and Klaus Mølmer*

Department of Physics and Astronomy, Aarhus University, Aarhus C, DENMARK

(*) dasari@phys.au.dk

Here we present a simple and robust scheme for deterministically entangling an ensemble of strongly interacting Rydberg atoms in the presence of dissipation [1]. While earlier approaches to generate entanglement via dissipation have been restricted mostly to the two-atom cases, with a combination of microwave driving between different Rydberg levels and a resonant laser coupling to a short lived atomic state, we obtain a dark steady state with entanglement between all atoms. The long-range resonant dipole-dipole interaction between different Rydberg states extends the entanglement beyond the van der Walls interaction range with perspectives for entangling very large and distant ensembles. Engineered dissipation [2] offers a route to entanglement which is robust towards various error mechanisms and to imprecise knowledge of system properties, such as the precise size of the ensemble.

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Poster 9

Tunable long-range interactions between atoms trapped near photonic crystals

J. S. Douglas[1*], *H. Habibian*[1], *A. V. Gorshkov*[2], *H. J. Kimble*[3], *and D. E. Chang*[1]

[1]ICFO-Institut de Ciencies Fotoniques, 08860 Castelldefels, Barcelona, Spain
[2]Joint Quantum Institute, NIST/University of Maryland, College Park, Maryland 20742, USA
[3]Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena, California 91125, USA

(*) james.douglas@icfo.es

Dipole-dipole interactions between neutral atoms are mediated by exchange of virtual photons and are typically weak over length scales much greater than the photon wavelength. These interactions can be strengthened by exciting the atoms to Rydberg states with large n. An alternative approach, which we propose here, is to alter the medium via which the virtual photons are exchanged, allowing long-range interactions between atoms at the lowest level of excitation, i.e., $n = 1$. We show this can be achieved by exploiting the powerful new platform of cold atoms trapped near nano-photonic systems. In particular, photonic crystals allow the exchange of photons between atoms to be highly modified in comparison to free space, leading to coherent long-range interactions with length scales up to hundreds of optical wavelengths. These systems may be used to study long-range interactions in many-body atomic systems as well as to realize effective long-range interactions between photons for non-local, non-linear optics.

Poster 10

Three-body Förster resonances in a frozen Rydberg gas

R. Faoro, B. Pelle, P. Cheinet, P. Pillet*

Laboratoire Aimé Cotton, CNRS, Univ Paris-Sud, ENS Cachan, Bât. 505, 91405 Orsay, France

(*) riccardo.faoro@u-psud.fr

E. Arimondo

Dipartimento di Fisica E. Fermi, Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy

Cold Rydberg atoms are a promising tool for studying few-body and many-body interaction because of their strong and long-range dipole-dipole interactions. Applying an external electric field, it is possible to induce a huge dipole moment and then tune dipole-dipole interactions. A well known example are Förster resonances [1] that consists in a transfer of energy between two different two-atoms states analogous to FRET in biology [2]. Further 4-atoms interaction have been observed in cold Cs Rydberg gas taking advantage of the proximity of two Stark-tuned Förster resonances [3].
We have observed 3-body Stark-tuned resonances in a cold Cs Rydberg gas for different principle quantum number n. The two processes that we have studied can be described by the following equations:

$$3 \times np \leftrightarrow (n+1)s + ns + np' \tag{1}$$

$$3 \times np' \leftrightarrow (n+1)s + ns + np \tag{2}$$

where np and np' differ respectively for $m_J = 1/2$ and $m_J = 3/2$. We excite the Rydberg state via a three-photon excitation starting from a Cs MOT, tuning the resonance with an external electric field [3].
These kind of resonances can be generalized for all values of n and in principle can be extended to all kind of atoms; it only requires $J > 1/2$ and the presence of a two-body resonance. This new FRET process could be used to design a 3-Qbit quantum gate or to provide an effective Quantum Non Demolition measure of entanglement between 2 atoms, measuring the 3rd. It could improve imaging techniques in biology that already use 2-body FRET [2] and new solar cell technology which already tries to mimic light-harvesting that is ruled by FRET.

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Poster 11

Dipolar exchange in interacting Rydberg gases

Miguel Ferreira-Cao,Vladislav Gavryusev, Georg Günter, Hanna Schempp, Shannon Whitlock and Matthias Weidemüller*

Physikalisches Institut, Universität Heidelberg

(*)ferreira@physi.uni-heidelberg.de

Dipolar exchange interactions are important phenomena in quantum magnetism, spin models, polar molecules or molecular aggregates [1]. For example, the basic mechanism of Förster resonance energy transfer (FRET) has been studied in the context of dipole-mediated energy transport in light-harvesting complexes and quantum dots. Ultracold Rydberg atoms in combination with electromagnetically induced transparency (EIT) offer an ideal system to study dipolar energy transport under the influence of a controlled environment [2]. One interesting aspect is how energy transport is affected by the decoherence introduced by the EIT laser fields.

We are now experimentally pursuing the transition from classical to coherent transport, which could be realized by switching off the EIT lasers and using microwave driven Rydberg p states as impurities [3]. As a first step we have performed measurements of microwave driven Rabi oscillations between s and p Rydberg states. Dipolar exchange interactions lead to damping of the Rabi oscillations for high Rydberg densities. This system constitutes an elementary realization of a quantum spin model with long-range and anisotropic spin-spin interactions. Future measurements will focus on spatially and temporally resolving the spin distribution, possibly revealing the formation of spatially ordered phases and the effect of quantum coherent transport on spin dynamics.

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Poster 12

The latest news about ultralong-range Rydberg molecules

Anita Gaj, Alexander T. Krupp, Thomas Schmid, Philipp Ilzhöfer, Robert Löw, Sebastian Hofferberth, Tilman Pfau*

Stuttgart, Germany

(*) a.gaj@physik.uni-stuttgart.de

Scattering between a Rydberg electron and ground state atoms can lead to the formation of ultralong-range Rydberg molecules in an ultracold gas. We will report on the creation of D-state and S-state molecules with high principle quantum numbers n ranging from 40 to 111. With increasing principle quantum numbers we observe decreasing binding energies, resulting eventually in a broadening and a shift of the spectral lines. We selectively excite rovibrational states of D-state molecules and by that generate alignment of these molecules. We study their binding energies and the shape of the binding potential at the crossing of two m_j states in an external electric field. The degeneracy of the electronic orbitals leads to stronger binding energies and different symmetries of the bound molecular states.

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Poster 13

Aggregate formation in off-resonantly driven Rydberg gases

Martin Gärttner, David Schönleber, Jörg Evers*

Max-Planck-Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany

(*) marting@mpi-hd.mpg.de

The dynamics of a cloud of ultra-cold two-level atoms is studied at off-resonant laser driving to a Rydberg state. We find that resonant excitation channels lead to strongly peaked spatial correlations associated with the buildup of asymmetric excitation structures. These aggregates can extend over the entire ensemble volume, but are in general not localized relative to the system boundaries. We identify characteristic features in the spatial excitation density, the Mandel Q parameter, higher statistical moments, and the total number of excitations [1]. Moreover, the influence of decoherence on the aggregate formation mechanism is studied. We conclude that in the presence of strong decoherence the aggregates grow sequentially around an initial grain. In the strongly dissipative regime a rate-equation description can be employed. This allows us to study large ensembles of atoms and to directly compare our findings to recent experimental observations [2].

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Poster 14

Towards imaging of single Rydberg Atoms

Vladislav Gavryusev, Georg Günter, Hanna Schempp, Giulia Faraoni, Martin Robert-de Saint-Vincent, Miguel Ferreira-Cao, Shannon Whitlock, Matthias Weidemüller

Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Electronically highly excited (Rydberg) atoms constitute a system with long range interactions which allows to study many intriguing phenomena, ranging from quantum non-linear optics to dipole-mediated energy transport.

We demonstrate optical imaging of Rydberg atoms using the interaction enhanced imaging technique [1], which allows to follow spatially the evolution of the system. This method exploits interaction-induced shifts on highly polarizable excited states of probe atoms, that can be spatially resolved via an electromagnetically induced transparency resonance. With this novel tool we observe the migration of Rydberg electronic excitations, driven by quantum-state changing interactions similar to Förster processes found in complex molecules. We find that the many-body dynamics of the energy transport is influenced by the environment, controlled through the laser parameters [2]. After having improved the optical resolution and CCD detector, we are progressing towards the observation of individual Rydberg atoms which would allow to resolve the spatial and temporal dynamics of the system.

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Poster 15

Dynamical Mean-Field Theory of Rydberg-dressed quantum gases in optical lattices

Andreas Geißler, Ivana Vidanovic, and Walter Hofstetter*

Institut für theoretische Physik, Goethe Universität, Frankfurt, Hessen

(*) geissler@th.physik.uni-frankfurt.de

As recent experiments have shown (e.g. [1, 2]), it is now possible to investigate Rydberg-dressed quantum systems in optical lattices with a large number of Rydberg excitations. Here we investigate these strongly correlated systems for the bosonic case, by applying the real-space extension of bosonic dynamical mean-field theory (R-BDMFT) to the two-species lattice Hamiltonian in two and three dimensions. We find new exotic quantum phases of lattice commensurate order, giving rise to a devils staircase in the filling as a function of the chemical potential. With increasing hopping, a nonzero condensate fraction starts to emerge, which can coexist with the spatial density-wave order, and thereby lead to a supersolid phase. A rich phase diagram is obtained in our simulations for experimentally realistic parameters.

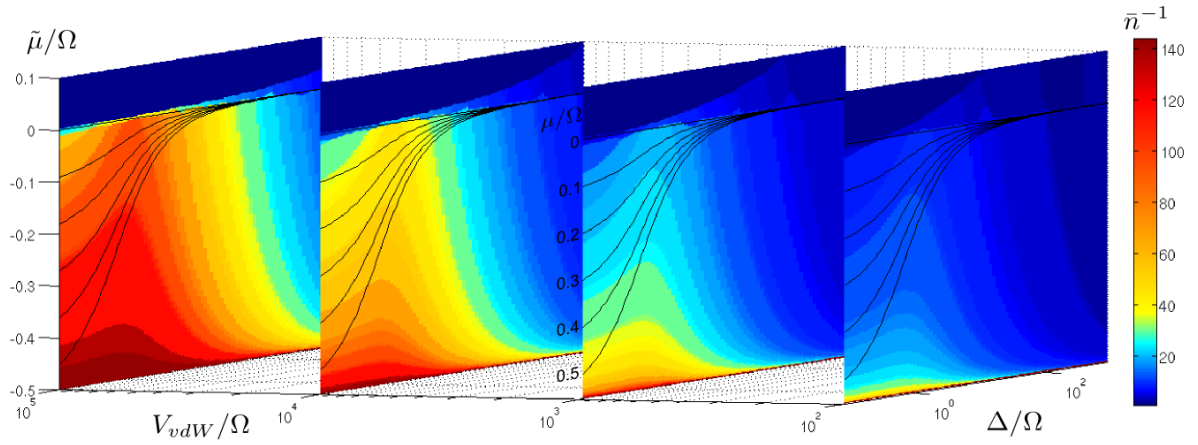

Figure 1: Phase diagram of Rydberg atoms in a two dimensional optical lattice in the limit of strong localization ($t/U \to 0$). Colors represent the inverse of the lattice filling $\bar{n} = \sum_i \langle n_{ground,i} + n_{rydberg,i} \rangle$. The actual chemical potential μ (black curves) is rescaled to $\tilde{\mu} = \mu \cdot (\Delta + \sqrt{1+\Delta^2})^{-1}$ with the detuning Δ given in units of the Rabi frequency Ω. The remaining axes are the detuning Δ in the blue detuned regime and the strength of the Van der Waals coupling $V_{vdW} = C^6/a^6$, with the lattice parameter a.

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Poster 16

Quantum Ice and dimer models with ultra-cold Rydberg atoms and ions

*Alexander W. Glätzle**

Innsbruck, Austria

(*) alexander.glaetzle@uibk.ac.at

We will present a discussion of quantum spin ice, which represents a paradigmatic example on how the physics of frustrated magnets is related to gauge theories. The goal is to assemble a system of cold Rydberg atoms and to design interactions that realize a toy model of quantum spin ice on a two-dimensional checkerboard lattice. In particular, we exploit the strong angular dependence of van der Waals interactions between high angular momentum Rydberg states. Together with the possibility of designing step-like potentials using ground state atoms weakly dressed by Rydberg states, we can implement Abelian gauge theories in a series of geometries, which could be demonstrated within state of the art experiments. [1]

In a parallel project we implement quantum simulators for various quantum spin models and frustrated magnets using a two-dimensional triagonal crystal of ions. Utilizing state dependent trapping frequencies of ions excited to a Rydberg state we can engineer localized modes, realizing exotic plaquette interactions imposing non-local energetic constraints. This allows to access a series of interesting models: 1) the Balents-Fisher-Girvin model where topological spin liquid phase has been predicted, 2) to observe Bose metal in a Honey-comb lattice with XY interactions and 3) to provide ion-lattice implementations for $U(1)$ lattice gauge theories.

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Poster 17

Rotational hybridization, and control of alignment and orientation in triatomic ultralong-range Rydberg molecules

Rosario González-Férez[*1,2], *H. R. Sadeghpour*[3] *and Peter Schmelcher*[2,4]

[1]Instituto Carlos I de Física Teórica y Computacional, and Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, 18071 Granada, Spain
[2]The Hamburg Center for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany
[3]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA
[4]Zentrum für Optische Quantentechnologien, Universität Hamburg, Germany

(*) rogonzal@ugr.es

We explore the electronic structure and rovibrational properties of an ultralong-range triatomic Rydberg molecule formed by a Rydberg atom and a ground state heteronuclear diatomic molecule. We focus here on interaction of Rb($27s$) Rydberg atom with KRb($N = 0$) diatomic polar molecule. There's significant electronic hybridization of Rb($n = 24, l \geq 3$) degenerate manifold. The polar diatomic molecule is allowed to rotate in the electric fields generated by the Rydberg electron and core as well as an external field. We investigate the metamorphosis of the Born-Oppenheimer potential curves, essential for the binding of the molecule, with varying electric field and analyze the resulting properties such as the vibrational structure and the alignment and orientation of the polar diatomic molecule [1].

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Poster 18

A theoretical framework for describing the coupling between Rydberg atoms and microwave circuits

Robert Jirschik, Sougato Bose and Stephen D. Hogan*

Department of Physics and Astronomy, University College London, Gower St., London WC1E 6BT, United Kingdom

(*) r.jirschik.13@ucl.ac.uk

The long radiative lifetimes and the sensitivity to microwave radiation of highly excited Rydberg states make them very well suited for hybrid approaches to quantum information processing involving gas-phase atoms and solid-state microwave circuits [1, 2, 3]. In this context, it is foreseen to exploit atoms in high Rydberg states as (1) probes of decoherence processes in solid-state circuits, (2) long-coherence-time quantum memories, and (3) a medium via which optical photons can be converted to microwave photons. To realize such schemes, it is important to develop a general theoretical framework in which the coupling between atoms, transmission line resonators and waveguides is accurately described in terms of the relevant experimental parameters.
This framework, which combines the theoretical description of coupled transmission line resonators [4, 5] with that of Rydberg atoms coupled to optical cavities [6], will be presented and used to investigate the propagation of microwave wave packets in a coplanar waveguide coupled to a transmission line resonator, which in turn is strongly coupled to an ensemble of Rydberg atoms.

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Poster 19

Collisional velocity dependence of hydrogen Rydberg atoms interacting with a surface

*Mike Kohlhoff**

Department of Chemistry, University of Oxford, Chemistry Research Laboratory, Oxford OX1 3TA, United Kingdom

(*) mike.kohlhoff@chem.ox.ac.uk

Rydberg hydrogen atoms undergo a charge transfer when brought into close proximity of a surface [1]. The process of surface ionisation is used to probe properties of a range of surfaces. The collisional velocities of the Rydberg atoms in the lab frame are comparatively high which can result in the surface ionisation process being masked by several effects. In order to minimise these ambiguities by achieving significantly lower collisional velocities, the surface experiment is extended with a surface-electrode design Rydberg-Stark decelerator on a chip [2]. In this configuration incoming Rydberg atoms are slowed down by traveling potential wells and directed towards the target surface.

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Poster 20

Ultralong-range Rydberg molecules in combined electric and magnetic fields

*Markus Kurz** and *Peter Schmelcher*

Zentrum für Optische Quantentechnologien, Luruper Chaussee 149, 22761 Hamburg, Germany

(*) mkurz@physnet.uni-hamburg.de

We investigate the impact of combined electric and magnetic fields on the structure of ultralong-range polar Rydberg molecules [1]. Our focus is hereby on the parallel as well as the crossed field configuration taking into account both the s-wave and p-wave interactions of the Rydberg electron and the neutral ground state atom. We show the strong impact of the p-wave interaction on the ultralong-range molecular states for a pure B-field configuration. In the presence of external fields the angular degrees of freedom acquires vibrational character and we encounter two- and three-dimensional oscillatory adiabatic potential energy surfaces for the parallel and crossed field configuration, respectively. The equilibrium configurations of local potential wells can be controlled via the external field parameters for both field configurations depending of the specific degree of electronic excitation. This allows to tune the molecular alignment and orientation. The resulting electric dipole moment is in the order of several kDebye and the rovibrational level spacings are in the range of $2 - 250$ MHz. Both properties are analyzed with of varying field strengths [2].

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Poster 21

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

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

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

(*) henning.labuhn@institutoptique.fr

Resonant energy transfers, the redistribution of an electronic excitation between two particles coupled by the dipole-dipole interaction, occur in a variety of chemical and biological phenomena [1], most notably photosynthesis. Here, we study, both spectroscopically and in the time domain, the coherent, dipolar induced exchange of electronic excitations between two single Rydberg atoms separated by a controlled distance, and brought in resonance by applying electric or microwave fields [2], for distances between the atoms between 8 and 50 μm. The coherent oscillation of the system between two degenerate pair states occurs at a frequency that scales as the inverse third power of the distance, the hallmark of dipole- dipole interactions [3]. We finally study the propagation of an excitation in a three-atom system. These results show our ability to actively tune and observe strong, coherent interactions in quantum many-body systems.

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Poster 22

Population-imbalanced fermionic polar molecules in bilayer system

*Hao Lee**[1,3], Daw-Wei Wang[1,2], G. V. Shlyapnikov[3,4]

[1] Physics Department and Frontier Research Center on Fundamental and Applied Sciences of Matter, National Tsing-Hua University, Hsinchu, Taiwan
[2] Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan
[3] Laboratoire de Physique Thorique et Modles Statistiques Théorique Modèles et Statistiques, Université Paris-Sud, CNRS, 91405 Orsay, France
[4] Van der Waals-Zeeman Institute, University of Amsterdam, Valckenierstraat 65/67, 1018 XE Amsterdam, The Netherlands

(*) s100022806@m100.nthu.edu.tw

We investigate population-imbalanced fermionic polar molecules tight in bilayer system in BCS regime. With choosing an oriented external electric field perpendicular to the layers, the interlayer dipole-dipole interaction can become the dominant term and well-controlled in BCS limit. While the imbalanced population of each layer makes Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state become achievable. Taking the influence of two-dimensional bound-state into consideration, we study the quantum and thermal phase diagram and relevant phase transition properties, and calculate the critical chemical potential difference and critical temperature for the FFLO state in weak-coupling regime.

Poster 23

Non-classical correlations in a class of spin chains with long-range interactions and exactly solvable ground states

Emanuele Levi, Igor Lesanovsky*

School of Physics and Astronomy, University of Nottingham, United Kingdom

(*) emanuele.levi@nottingham.ac.uk

We introduce a class of spin models with long-range interactions—in the sense that they extend significantly beyond nearest neighbors—whose ground states can be constructed analytically and have a simple matrix product state representation. This enables the detailed study of ground state properties, such as correlation functions and entanglement, in the thermodynamic limit. The spin models presented here are closely related to lattice gases of strongly interacting polar molecules or Rydberg atoms which feature an excluded volume or blockade interaction. While entanglement is only present between spins that are separated by no more than a blockade length, we show that non-classical correlations can extend much further and analyze them through quantum discord [1]. We furthermore identify a set of seemingly critical points where the ground state approaches a crystalline state with a filling fraction that is given by the inverse of the blockade length. These states are analogous to the ones studied analytically in [2], and those recently observed in experiments [3]. We analyze the scaling properties in the vicinity of this parameter region and show that the correlation length possesses a non-trivial dependence on the blockade length.

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Poster 24

Trapped Rydberg ions

Weibin Li[*1], *Alexander W. Glaetzle*[2], *Rejish Nath*[2], *and Igor Lesanovsky*[1]

[1]School of Physics and Astronomy, the University of Nottingham, Nottingham NG7 2RD, UK
[2] Institute for Theoretical Physics, University of Innsbruck and Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria

(*) weibinli@gmail.com

In this work, we exploit the unique properties of electrically trapped ions in their Rydberg states and make use of these properties for quantum information applications. We will show that even the excitation of a single Rydberg ion from an ion crystal in a Paul trap can in general not be described within a single particle picture [1]. This effect is due to a strong coupling between the electronic dynamics and the vibrational modes of the ion crystal and counterpart in experiments with neutral atoms. We will demonstrate that this effect can find applications in the creation of non-classical motional states of trapped ions and that it can be employed to dynamically shape the structure of vibrational ion crystal modes for the application in parallel quantum information processing [2]. We will further demonstrate that a fast quantum gate can be built by using the strong dipolar interaction between Rydberg ions [3].

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Poster 25

EMERGENCE OF UNIVERSALITY IN THE DYNAMICS OF DISSIPATIVE RYDBERG GASES

M. Marcuzzi, E. Levi, S. Diehl, J. P. Garrahan and I. Lesanovsky*

(*) School of Physics and Astronomy, University of Nottingham, UK

(*) matteo.marcuzzi@nottingham.ac.uk

Employing a uniform mean-field approach, we study the dynamics of a dissipative gas of Rydberg atoms [1] and analyse the previously-found transition from a stable to a bi-stable phase [2]. We identify a critical point and determine the corresponding universality class, which turns out to be "model A" (or "Glauber-Ising"), as it features a non-trivial Z_2 symmetry with a non-conserved order parameter. This sheds light on some relevant aspects of dynamical transitions in Rydberg gases. In particular, it permits a qualitative and partly quantitative understanding of a recent experiment [3] which observed bistable behaviour as well as power-law scaling of the relaxation time. The latter emerges not due to critical slowing down in the vicinity of a second order transition, but from the non-equilibrium dynamics near a so-called spinodal line.

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Poster 26

Quantum 1-spin facilitated models with Rydberg atoms in optical lattices

Marco Mattioli (⋆), Wolfgang Lechner, Alexander G. Glätzle, Peter Zoller

Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, 6020 Innsbruck, Austria
Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria

(⋆) marco.mattioli@uibk.ac.at

We propose a quantum simulation of a one-dimensional 1-spin facilitated model with Rydberg atoms in optical lattices. Facilitated Spin Models (FSMs) [1] are well known to capture glass features like dynamical heterogeneities and critical slowing down of relaxation times.
If each atom is driven with a strong transition from the ground state to an excited rapidly decaying state, and with a weak off-resonant transition to a metastable Rydberg state [2], interactions between Rydberg levels belonging to neighbouring atoms might induce effective kinetic constraints typical of a certain class of FSM. These kinetic constraints reduce the number of 'allowed' transitions between different configurations of Rydberg excitations; critical slowing down of the dynamics of such excitations occur, thus preventing thermalisation.
Our results of quantum Monte-Carlo trajectory simulations show that two-time correlators, like e.g. the persistence function, manifest intermediate plateaus similar to that of dynamically arrested glasses. Furthermore, at very short times, the facilitated lattice sites (i.e., the ones next to a Rydberg excited atom), relax much faster than non-facilitated lattice sites.
We finally studied the interplay and coexistence between glass and many-body localisation transition [3], by adding to the detuning with respect to the Rydberg state a second (spatially) random detuning.

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Poster 27

Coherent ion-transport via Rydberg dressing of an atomic optical lattice

*Rick Mukherjee**

Max Planck Institute for the Physics of Complex systems, Dresden

(*) rick@pks.mpg.de

Simultaneous trapping of Rydberg atoms/ions along with ground state atoms is made possible though the use of alkaline-earth atoms. We study the dynamics of an ion in an optical lattice of alkaline-earth atoms with single atom per site by weakly coupling to the Rydberg state. The effect of the charged particle on these highly excited states results into a complex structure of molecular potential curves of a stable mesoscopic molecular ion which propagates through the lattice in strong reminiscence of an exciton whose effective mass is defined by the laser parameters. A detailed analysis on the effect of the motional states on the dynamics provides a criterion that distinguishes coherent dynamics from incoherent dynamics. This offers unique opportunities to steer coherent charge transport and implement, e.g. a range Holstein-Hubbard type Hamiltonians in optical lattices.

Poster 28

Rydberg excitation of Rubidium atoms in magnetic microtraps

Julian Naber, L. Torralbo-Campo, A. La Rooij, M. Soudijn, N.J. van Druten, H.B. van Linden van den Heuvell and R.J.C. Spreeuw*

Amsterdam, Netherlands

(*) j.b.naber@uva.nl

Atoms excited to high lying Rydberg states offer a variety of applications in fields like Quantum Information and Quantum Simulation. We want to exploit those properties of Rydberg atoms in our experimental system which is an array of Ioffe-Pritchard type microtraps realized by a patterned permanently magnetized film on an atom chip. The array has a period of 10μm which is comparable to the dipole blockade radius between Rydberg atoms in neighbouring trap sites. We recently demonstrated successful trapping of ^{87}Rb atoms in those structures [1]. Rydberg atoms in our traps can yield interesting spectroscopic properties [2], can be used as a surface probe [3] and are a natural candidate for a quantum information platform [4]. We also hope to see effects like crystalline ordering [5] and coherent excitation dynamics [6]. The atoms will be excited in a two-photon process involving narrow linewidth lasers. Single-site addressing will be ensured by shaping the excitation light with a Spatial Light Modulator. Finally the setup comprises a set of phase-locked lasers for Raman transitions on the Qubit realized in the ground states of Rb.

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Poster 29

Long coherence times for Rydberg qubits on a superconducting atom chip

C. Hermann-Avigliano [1], *R. Celistrino Teixeira* [1], *T.L. Nguyen* [1,*], *T. Cantat-Moltrecht* [1], *G. Nogues* [2], *I. Dotsenko* [1], *S. Gleyzes* [1], *J.M. Raimond* [1], *S. Haroche* [1] *and M. Brune* [1]

[1] Laboratoire Kastler Brossel, ENS, UPMC-Paris 6, CNRS
Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France.
[2] Univ. Grenoble Alpes, Inst. NEEL, F-38042 Grenoble, France.

(*) thanh.long.nguyen@lkb.ens.fr

Rydberg atoms are the focus of a thriving experimental and theoretical activity. Many proposals for quantum simulation of condensed matter systems and quantum information processing exploit their strong, long-range, dipole interaction. Exciting Rydberg atoms in a BEC prepared on a superconducting atom chip [1], is particularly promising in this context. It opens the route to a hybrid interface between on-chip quantum superconducting circuits and atomic ensembles.

Manipulating Rydberg atoms with an atom chip, however, requires a good control of electric field nearby a metallic surface, as highly excited atoms are very sensitive to Stark effect. The problem is more crucial as soon as there is formation of dipolar patches due to uncontrolled Rb deposition on the chip surface [2, 3, 4, 5]. A simple solution for our particular experiment with superconducting atom chip consists in covering all essential metallic surfaces by a layer of Rb. Thanks to that we could demonstrate unprecedented long coherent manipulation for transition between adjacent Rydberg levels with principal quantum number $n \approx 60$, by using standard microwave spectroscopy techniques (Rabi oscillation, Ramsey interference and spin echo). The measured coherence time is in the ms range, exceeding the lifetime of Rydberg atoms themselves [6]. This reveals new perspectives for studying the collective excitation dynamics of ultra cold atomic ensemble in the strong dipole blockade regime.

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Poster 30

TOWARDS A STRONGLY INTERACTING GAS OF COLD STRONTIUM RYDBERG ATOMS

*Ingo Nosske**

Shanghai, P.R. China in collaboration with Heidelberg, Germany

(*) nosske@physi.uni-heidelberg.de

In our new laboratory in Shanghai, we aim to cool down strontium atoms via laser cooling techniques close to quantum degeneracy and to perform first pilot experiments on an ultracold Rydberg gas. Strontium, as a two-electron system, offers novel opportunities as compared to previous investigations on ultracold Rydberg gases done with single-electron atoms.

We will laser cool and trap strontium atoms close to quantum degeneracy in a broad and a narrow linewidth magneto-optical trap. The feasibility of these laser cooling techniques has already been demonstrated and lead for example to a very fast Bose-Einstein condensate (BEC) creation cycle time [1]. Two-photon excitation schemes [2] will be applied to prepare Rydberg states for the study of correlations induced by the Rydberg blockade [3]. Its influence on the dynamics and properties of an ultracold plasma will be explored. In addition, we will demonstrate trapping of Rydberg atoms by optical dipole forces on the inner core electron.

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Poster 31

Relaxation of interacting many-body systems under purely dissipative quantum dynamics

Beatriz Olmos, Igor Lesanovsky and Juan P. Garrahan

School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK

(*) beatriz.olmos-sanchez@nottingham.ac.uk

We study the relaxation dynamics of quantum many-body systems that undergo purely dissipative dynamics through non-classical jump operators that can establish quantum coherence. We contrast the relaxation dynamics of this class of systems with those evolving via classical rate equations towards a stationary state with the same values of diagonal or "classical" observables as in the quantum system but where coherences are absent. We focus in particular on spin systems whose dynamics becomes correlated and complex due to dynamical constraints, inspired by kinetically constrained models (KCMs) of classical glasses. We show that in the quantum case the relaxation of the coherences can be orders of magnitude slower than that of diagonal observables. Finally, we show that the relaxation of strongly interacting Rydberg atoms under electromagnetically induced transparency (EIT) conditions can indeed, in an appropriate limit, be described by such a purely dissipative dynamics with non-classical jump operators. We establish a connection between the Rydberg system and the discussed KCMs and investigate the limitations of using a classical rate equation model to capture the non-equilibrium behaviour of this system.

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Poster 32

CONTROLLED FEW-BODY FÖRSTER RESONANCES IN A FROZEN RYDBERG GAS

Bruno Pelle, Riccardo Faoro, Alexandre Zuliani, Patrick Cheinet, Pierre Pillet*

Laboratoire Aimé Cotton, CNRS, Université Paris-sud, Bât. 505, 91405 Orsay, France

(*) patrick.cheinet@u-psud.fr

Resonant energy transfer in Rydberg atoms is well known to enhance 2-body interactions between adjacent atoms [1], which is also called Förster resonances in analogy with the biological process known as FRET. We use this process to realize new resonant 3-body or n-body interactions extending the pre-existing 2-body FRET processes in cold Rydberg atoms. Compared to previous results on a 4-body interaction [2] which was a coincidence product of two independent 2-body FRET processes in cesium, this new scheme can be generalized to any atoms having a total angular momentum $J > 1/2$.

Experimentally, we realize a magneto-optical trap in which atoms can be considered as frozen compared to the lifetime of the Rydberg state. Tuning a static electric field, 2-body Förster resonances can be observed due to the Stark shift of the Rydberg levels. A Förster resonances results then in a transfer of population between the different states involved in this energy transfer, as expressed in the equation 1 for a 2-body Förster resonance:

$$2 \times np \leftrightarrow ns + (n+1)s. \tag{1}$$

Considering a density high enough in order to allow the occurrence of more than two excited Rydberg atoms close to each others, we can expect a 3-body interaction that can be expressed as a 3-body Förster resonance in the equation 2:

$$3 \times np_{3/2}m \leftrightarrow ns + (n+1)s + np_{3/2}m' \tag{2}$$

where m and m' are two different magnetic quantum numbers.

On the Fig. 1, this 3-body Förster resonance is visible at $\mathrm{F} = 6.61$ V/cm with a large transfer to the s states, while the 2-body Förster resonance appears at $\mathrm{F} = 6.89$ V/cm for the principal quantum number $n = 32$. This difference in energy exchange between those two resonances can be explained by the change of the magnetic quantum number of the third atom involved in the interaction. As expected, we have observed the presence of this 3-body Förster resonance for any $np_{3/2}$ states in caesium.

Our observations are likely to have implications in various domains, from quantum physics to biology and new materials. This new FRET process could be used to design a 3-Qbit quantum gate as proposed in [3] or to provide an effective Quantum Non Demolition measurement of entanglement between 2 atoms, measuring the third one. FRET is also widely used in biology as an imaging tool [4] which could be extended using additional molecules inducing 3-body FRET. Finally, 3-body FRET could help improving new solar cell technology [5] which already tries to mimic light-harvesting [6].

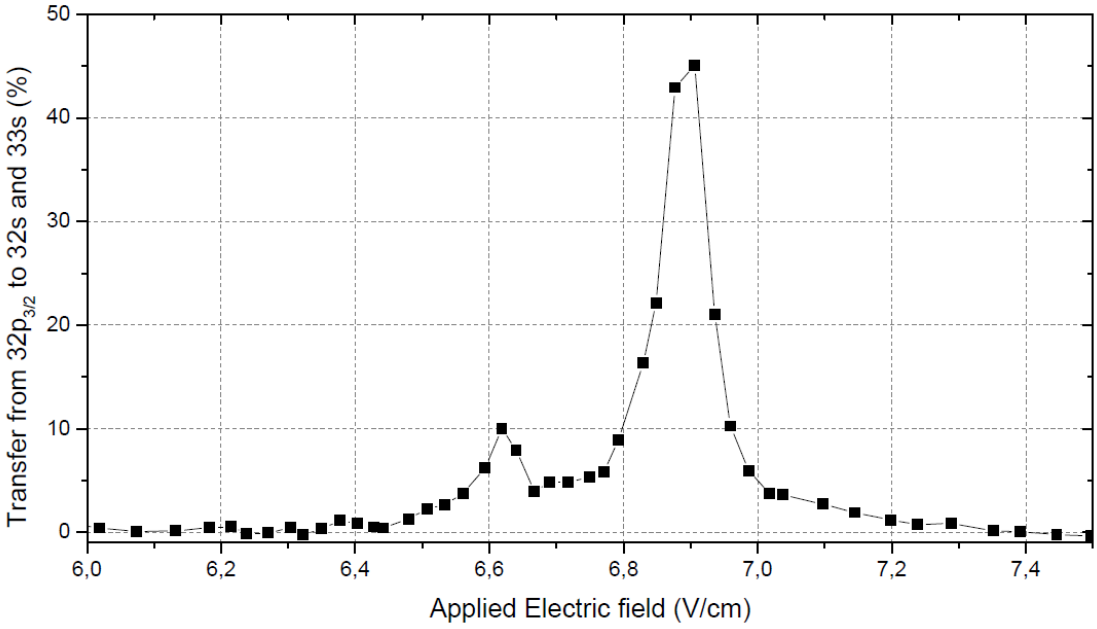

Figure 1: Transfer efficiency from $32p_{3/2}$ to $32s$ and $33s$ in percent as a function of the applied electric field. The 2-body Förster resonance is expected at $\mathrm{F} = 6.89$ V/cm while the 3-body Förster resonance is calculated to be at $\mathrm{F} = 6.61$ V/cm.

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Poster 33

Formation of penning lattice in strongly correlated ultra-cold molecular plasma

Hossein Sadeghi and Edward R. Grant

Vancouver, Canada

hossein@chem.ubc.ca

High density ultra-cold molecular plasmas provide a novel laboratory for the study of Columb correlation, many-body effects, and exotic states of matter. Laboratory plasmas span a range of density and temperature, from a strongly coupled regime that can form crystals, to plasmas that are cold and non-correlated. As a result of disorder induced heating, ultracold neutral plasmas, created by photoionization to form with moderate correlation, generally experience a temperature rise that reduces Γ to a value less than one. Our experiment starts with a state-selected Rydberg gas prepared by exciting nitric oxide molecules in a supersonic beam. Penning ionization with dissociation initiates an electron-impact avalanche that, for certain initial principal quantum numbers, forms a plasma with an ordered ion distribution. This plasma maintains a state of ion-ion correlation which has an observable effect on the rate of plasma expansion. In the subsequent avalanche, the spatially correlated release of electrons from Rydberg molecules establishes an initial electron-ion correlation. In preliminary MD simulations, we observe an effect of this natural bias in electron position on the initial electron temperature of plasmas that evolve from a cold Rydberg gas.

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Poster 34

Classical damping of a nano-mechanical oscillator using electromagnetically induced transparency

Adrián Sanz Mora, Alexander Eisfeld, Sebastian Wüster, and Jan-Michael Rost*

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

(*) adnsmora@pks.mpg.de

We investigate the mutual coupling of a three-level ultracold atomic gas and a classical nano-mechanical oscillator via electromagnetic radiation. The atoms interact with the probe- and control beams that electromagnetically induce transparency (EIT) [1] in the gas. Both of these couple to the mechanical motion of a vibrating mirror via radiation pressure forces. The power of the probe light field is modulated by the absorption of the atoms, providing coupling of the gas to the mirror. The control light field is phase-modulated by the mirror vibrations, providing coupling of the mirror to the gas. For classical light fields and simplified response of the gas, we explore damping or driving of the mirror. By assuming that the third level is a Rydberg state, our setup can interface optomechanics [2] with Rydberg physics.

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Poster 35

Observation of dipole-dipole and dipole-quadrupole interactions between pairs of ultracold Cesium Rydberg atoms.

Heiner Saßmannshausen, Johannes Deiglmayr, Pierre Pillet and Frédéric Merkt*

ETH Zürich, Laboratory of Physical Chemistry, Vladimir-Prelog-Weg 2, CH-8093 Zürich, Switzerland
Laboratoire Aimé Cotton du CNRS, F-91405 Orsay

(*) heiner.sassmannshausen@phys.chem.ethz.ch

We have used a pulse-amplified frequency-doubled ring dye laser with a 140 MHz Fourier-transform-limited bandwidth and a wavelength of around 320 nm to excite ultracold cesium atoms to $n\mathrm{p}_{3/2}$ Rydberg states with principal quantum numbers n between 22 and 180. We performed measurements at low atom density ($\approx 10^9$ atoms/cm^3) on atoms released from a magneto-optical trap and at increased density ($\approx 10^{12}$ atoms/cm^3) after loading the atoms in a crossed optical dipole trap. At low Rydberg-atom density and after compensating electric and magnetic stray fields to $\approx$1 mV/cm and 2 mGs, respectively, millimetre-wave spectra of transitions between Rydberg states were recorded with a spectral resolution of 20 kHz [1].
At high densities, interactions between Rydberg atoms dominate the dynamics of the cold Rydberg gas, leading to effects such as, e.g., the excitation blockade [2] in the case of excitation with narrow-band lasers and rapid many-body ionization [3] in the case of pulsed broad-band excitation. We utilize the observed interaction-induced ionisation to detect Rydberg states with principal quantum number down to $n = 22$ which cannot be directly field ionised in our setup. Under these conditions, and using laser intensities where the atomic $n\mathrm{p}_{3/2} \leftarrow 6\mathrm{s}_{1/2}$ transitions are saturated, additional lines in the Rydberg spectrum are observed that cannot be assigned to single-atom transition frequencies. By the comparison of their spectral positions with calculated pair energies, their Stark shift and modeling of the excitation mechanism we attribute these lines to the excitation of $n\mathrm{s}_{1/2}(n+1)\mathrm{s}_{1/2}$ and $n\mathrm{s}_{1/2}(n-3)\mathrm{f}$ pair states (with $22 < n < 36$). These pair states are dipole-dipole and dipole-quadrupole coupled, respectively, to corresponding $n\mathrm{p}_{3/2}n\mathrm{p}_{3/2}$ pair states and are therefore accessible via two-photon transitions from a pair of cesium atoms in the $6\mathrm{s}_{1/2}$ electronic ground state.

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Poster 36

Spectral Signatures of Excitation Transport in Ultra-Cold Rydberg Gases

*Torsten Scholak**

Chemical Physics Theory Group, Department of Chemistry and Center for Quantum Information and Quantum Control, University of Toronto, Toronto, Canada M5S 3H6

Physikalisches Institut der Albert-Ludwigs-Universität, Hermann-Herder-Str. 3, D-79104 Freiburg, Germany

Thomas Wellens, Andreas Buchleitner

Physikalisches Institut der Albert-Ludwigs-Universität, Hermann-Herder-Str. 3, D-79104 Freiburg, Germany

(*) torsten.scholak@googlemail.com

The spectral signatures of excitonic energy transfer in ultra-cold Rydberg gas clouds are studied numerically, in the framework of random matrix theory, and via self-consistent diagrammatic techniques. Rydberg gases are made up of randomly distributed, highly polarizable atoms that interact via strong long-range dipolar forces. Dynamics in such a system is fundamentally different from cases in which the interactions are short-range. In the spectral level spacing statistics, we find evidence for a critical energy that separates delocalized eigenstates from states that are localized at pairs or clusters of atoms separated by less than the typical nearest-neighbor distance. We argue that the dipole blockade effect in Rydberg gases can be leveraged to manipulate this transition across a wide range: As the blockade radius increases, the degree of localization in the system is reduced. At the same time, the spectral statistics—in particular, the density of states and the nearest neighbor level spacing statistics—change their approximate agreement from the 1-stable Lévy to the Gaussian orthogonal random matrix ensemble. Deviations to random matrix statistics are identified to stem from correlations between atomic interactions that lead to an asymmetry of the spectral density and are also shown to have a profound influence on localization. We solve approximations to the self-consistent Matsubara-Toyozawa locator expansion that incorporate these effects. [1]

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Poster 37

Preparing highly excited states with pulsed ladder schemes in atom vapours at room temperature

Nikola Šibalić, Christopher G. Wade, James Keaveney, Charles S. Adams, Kevin J. Weatherill*

Joint Quantum Center (JQC) Durham-Newcastle, Department of Physics, Durham University
South Road, Durham, DH1 3LE, United Kingdom

nikola.sibalic@durham.ac.uk

Strong atom-atom interactions in highly excited atom gases provide new possibilities for exploring cooperative quantum behaviour [1] and implementing optical nonlinearities at the single photon level [2]. Recent experiments demonstrated that even in thermal atomic samples it is possible to achieve coherent excitation of the Rydberg atoms [3], as well as to observe nonequilibrium phase transitions arising from the strong atom-atom interactions [4]. Aiming to add to this work in hot Rydberg samples, we are developing a new excitation scheme for reaching high lying states in atomic vapours at room temperature. Using a 3-step excitation scheme [5], highly excited states will be prepared with a train of short, high Rabi frequency laser pulses. A review of the basic ideas behind this scheme, and current progress will be presented.

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Poster 38

Ultracold Atomic Ensembles on a Magnetic-Film Atom Chip for Quantum Information

Maarten L. Soudijn, L. Torralbo-Campo, J. Naber, A. La Rooij, N. J. van Druten, H. B. van Linden van den Heuvell and R. J. C. Spreeuw*[†]

WZI - IoP - University of Amsterdam, The Netherlands

(*) M.L.Soudijn@uva.nl (†) R.J.C.Spreeuw@uva.nl

Using an FePt magnetic-film atom chip we load a lattice of microtraps with ultracold ^{87}Rb atoms, a promising platform for Quantum Information purposes [1]. We discuss the latest results of our experiment with these cold atomic ensembles in a lattice of Ioffe-Pritchard type microtraps. Recently we have demonstrated the loading of about 600 lattice sites with about 400 atoms/trap and an average temperature of T=30 μK [2]. Our aim is to develop this system as a scalable platform for quantum simulation and quantum information science, by making use of long-range dipole-dipole interactions between Rydberg atoms [3, 4].

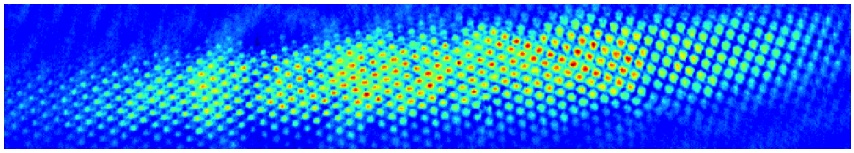

Figure 1: Absorption image of an ultracold atomic cloud loaded into a lattice of microtraps based on a magnetic film atom chip, forming hexagonal and square lattice sites.

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Poster 39

Rydberg Atoms as Surface Probes

*Atreju Tauschinsky**, Jemma Gibbard, Mike Kohlhoff, Mark Ford and Tim Softley

Department of Chemistry
University of Oxford

(*) Atreju.Tauschinsky@chem.ox.ac.uk

Rydberg atoms are well known for their large polarisabilities and strong coupling to the environment. We have investigated the suitability of Hydrogen Rydberg atoms as probes of electronic surface states, observing interesting effects in the surface ionisation profiles. In particular, we have looked at the behaviour of Rydberg atoms approaching a Cu (100) surface. Cu (100) has a band gap along the surface normal and a series of image states at the surface-vacuum interface. Resonance effects in the surface ionisation dynamics are therefore predicted at fields corresponding to the image state energies. We present measurements of ionisation rates for a clean Cu (100) surface as a function of both principal quantum number and incident velocity of the Rydberg beam.

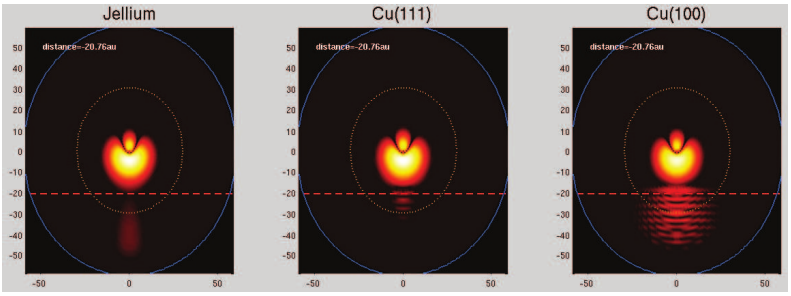

Figure 1: Rydberg state wavefunctions for $n = 2$ approaching a free electron metal, Cu (111) or Cu(100) surface.

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Poster 40

Single-photon transistor mediated by inter-state Rydberg interaction

Christoph Tresp, Hannes Gorniaczyk, Ivan Mirgorodskiy, Johannes Schmidt, and Sebastian Hofferberth*

5th Institute of Physics, University of Stuttgart

(*) c.tresp@physik.uni-stuttgart.de

Electromagnetically induced transparency (EIT) incooperating a long-lived Rydberg state can result in collective optical nonlinearities mediated by the long-range interaction between Rydberg atoms, which enables manipulation of light fields on the single photon level. Recent experimental results based on this novel approach include efficient single photon generation, demonstration of attractive interactions between photons, and efficient all-optical switching.

We present our realization of an all-optical transistor based on the mapping of gate and source photons into strongly interacting Rydberg excitations with different principal quantum numbers in an ultracold atomic ensemble. We obtain a record switch contrast of 40% for a coherent gate input with mean photon number one and demonstrate attenuation of source transmission by over 10 photons with a single gate photon. We use our optical transistor to demonstrate the nondestructive detection of a single Rydberg atom with a fidelity of 0.72(4) [1].

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Poster 41

On and off-resonant excitation dynamics of strongly correlated Rydberg systems

María M. Valado [1,2], *Cristiano Simonelli* [2], *Ennio Arimondo* [1,2,3], *Donatella Ciampini* [1,2,3], *Oliver Morsch* [1,2]

[1]CNR-INO, Via G. Moruzzi, 1, 56124 Pisa, Italy

[2]Dipartimento di Fisica 'E. Fermi', Università di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

[3]CNISM UdR Dipartimento di Fisica 'E. Fermi', Università di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

(*) valado@df.unipi.it

Ultracold Rydberg gases represent ideal candidates for studying strongly interacting many-body systems. Here we present a study on the formation and dynamics of strongly correlated structures of atoms excited to Rydberg states both for resonant and off-resonant regimes.

Under resonant laser driving conditions, the strong interactions between Rydberg atoms become manifest either as spatial correlations compatible with a radius of blockade around an excited atom or through a reduction of fluctuations leading to sub-Poissonian statistics [1]. In our experiments, we excite Rydberg atoms in a cold cloud and change the interaction strength between them by varying the mean interparticle distance. These interactions lead to kinetic constraints which slow down the excitation dynamics, as theoretically predicted in [2].

In the off-resonant excitation regime, an atom can be shifted into resonance by another one already excited to a Rydberg state if the interaction energy matches the energy mismatch of the laser excitation: $V_{vdW} = C_6/r^6 = \hbar\Delta$. In this context, the existence of an initial seed is enough to start a chain reaction, leading to an avalanche of Rydberg excitations. Thus, by using an initial Rydberg excitation as a seed we manage to control the off-resonant excitation process. Furthermore, making use of the information contained in the histograms of the full counting distributions obtained varying the density or the detuning, we can identify the main features between resonant and off-resonant regime [3].

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Poster 42

Low-energy behaviour of strongly-interacting bosons on a flat-banded lattice above the critical filling factor

Manuel Valiente

Heriot-Watt University, Edinburgh UK

M.Valiente_cifuentes@hw.ac.uk

Bosons interacting repulsively on a lattice with a flat lowest band energy dispersion may, at su?fficiently small fi?lling factors, enter into a Wigner-crystal-like phase. This phase is a consequence of the dispersionless nature of the system, which in turn admits single-particle localised eigenstates. We investigate one of these systems loaded with strongly repulsive bosons at filling factors in?finitesimally above the critical point where the crystal phase is no longer the ground state. We fi?nd, in the hard-core limit, that the crystal retains its structure in all but one of its cells, where it is broken. The broken cell corresponds to an exotic kind of two-particle bound state, which becomes delocalised. We investigate the excitation spectrum of the system and ?find that the bound-state behaves as a single particle hopping on an eff?ective lattice with a distinct geometry. Thus, the addition of a single boson to a flat-banded system at critical ?lling is found to be enough to make kinetic behaviour manifest.

Poster 43

Spin-1 quantum magnets from multi-level Rydberg atoms

Rick van Bijnen[*1], *Rejish Nath*[2,3], *Volckmar Nebendahl*[3] *Igor Lesanovsky*[4], *Andreas Läuchli*[3], *Thomas Pohl*[5]

[1]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany
[2] Indian Institute of Science Education and Research, Pune, India
[3] Institut für Theoretische Physik, Universität Innsbruck, Innsbruck, Austria
[4] School of Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom

(*) rvb@pks.mpg.de

Ultracold, highly excited Rydberg atoms exhibit extremely strong and tunable interactions, making them promising candidates for quantum information and quantum simulation purposes. For instance, optical coupling of the ground and a Rydberg state of ultracold atoms in a lattice geometry directly yields an effective spin-1/2 system with long-range Ising-type interactions, which has attracted significant fundamental interest in recent years.

Here, we show how the quantum simulation toolbox can be expanded towards new classes of quantum magnets, with a minimal increase in the complexity of corresponding experiments by considering optical coupling to one additional Rydberg level. This yields an effective spin-1 system, which exhibits a range of nonclassical, highly entangled ground states which are otherwise inaccessible in previous settings. We discuss additional interactions appearing in this system for varying principal quantum numbers, and investigate the resulting phase diagrams.

Poster 44

Towards Rydberg-mediated interactions on an atom chip

N.J. van Druten, N. Cisternas, J.J.M. de Hond, R.J.C. Spreeuw and H.B. van Linden van den Heuvell*

Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, The Netherlands

(*) N.J.vanDruten@uva.nl

Atom chips are a convenient, fast and compact means to generate ultracold and quantum-degenerate gases. In particular, it is relatively easy to produce one-dimensional Bose-Einstein condensates. We are extending the "Celsius" atom chip setup at the University of Amsterdam [1, 2] to allow for Rydberg excitation of elongated Bose-Einstein condensates. Rydberg-mediated interactions are very promising for quantum simulation and quantum information processing in this geometry [3, 4]. We plan to explore a variety of opportunities, using either direct excitation or Rydberg dressing, including the possibility of adiabatic crystal formation [5].

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Poster 45

Wireless Network Control of Interacting Rydberg Atoms using Spatial Light Modulators

Edgar Vredenbregt, Jaron Sanders, Rick van Bijnen**, and Servaas Kokkelmans*

Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, Netherlands
(*) Department of Mathematics and Computer Science, Eindhoven University of Technology
(**) Current address: Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Strasse 38, 01187 Dresden, Germany

We explore a relation between the dynamics of ultracold Rydberg gases and certain wireless random-access networks. Wireless networks show blockade phenomena due to interference, much like Rydberg atoms for which the blockade is due to an interaction-induced level shift. Surprisingly, under certain conditions their dynamics can be described with the same equations, both resulting in complicated large-scale system behavior. As a result, mathematical techniques initially developed for wireless networks can be applied to Rydberg gases. E.g., a description of wireless networks can explain how a Rydberg gas can be driven into crystal formation. As an extension, we apply an algorithm that determines Rabi frequencies (laser intensities) such that particles in the Rydberg gas are excited with specific target excitation probabilities, which leads to control over mixed-state populations. This can be of interest to (for example) mixed state quantum computing, which is somewhere in between classical and quantum computing.

A precise control over the locations of the excitations is then a necessity. Experimentally, we add structure to the excitation laser light by using a spatial light modulator [**?**]. In principle, arbitrary geometries can be constructed in this way, such as lattice structures that are more flexible than optical lattices. Shaping the excitation laser light with phase modulation requires optical patterns to be delivered inside a vacuum chamber, which may be hampered by optical aberrations. Here we demonstrate a method to characterise and correct phase aberrations, significantly improving the quality of the light field at the location where the Rydberg atoms are formed.

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Poster 46

Dynamical crystallization in a low-dimensional Rydberg gas

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

[1]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[2]Laboratoire Charles Fabry, Institut d'optique Graduate School - CNRS - Université Paris Sud, 91127 Palaiseau, France
[3]Max-Planck-Institut für Physik komplexer Systeme, 01187 Dresden, Germany
[4]Ludwig-Maximilians-Universität, Fakultät für Physik, 80799 München, Germany

(*) johannes.zeiher@mpq.mpg.de

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 [1]. 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 [2].

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Poster 47

Full counting statistics of laser excited Rydberg aggregates in a one-dimensional geometry

G. Zürn[1] *H. Schempp, G. Günter*[1]*, M. Robert-de-Saint-Vincent*[1]*, C. S. Hofmann*[1]*, D. Breyel*[2]*, A. Komnik*[2]*, D. W. Schönleber*[3]*, M. Gärttner*[2,3]*, J. Evers*[3]*, S.Whitlock*[1]*, and M.Weidemüller*[1]

[1] Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, Heidelberg, Germany
[2] Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, Heidelberg Germany
[3] Max-Planck-Institut f ur Kernphysik, Saupfercheckweg 1, Heidelberg, Germany

(*) gerhard.zuern@physi.uni-heidelberg.de

We experimentally study the full counting statistics of few-body Rydberg aggregates excited from a quasi-one-dimensional atomic gas [1]. We measure asymmetric excitation spectra and increased second and third order statistical moments of the Rydberg number distribution, from which we determine the average aggregate size. Estimating rates for different excitation processes we conclude that the aggregates grow sequentially around an initial grain. Direct comparison with numerical simulations confirms this conclusion and reveals the presence of liquid-like spatial correlations. Our findings demonstrate the importance of dephasing in strongly correlated Rydberg gases and introduce a way to study spatial correlations in interacting many-body quantum systems without imaging.

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