# Symposium Ultracold Rydberg Atoms and Molecules (SYRA)

jointly organized by
the Quantum Optics and Photonics Division (Q) and
the Atomic Physics Division (A)

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# Overview of Invited Talks and Sessions

(lecture room V47.01 and V7.03)

## Invited Talks

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|---|---|---|---|---|
| SYRA 1.1 | Tue | 10:30–11:00 | V47.01 | **Quantum optics and quantum information with Rydberg excited atoms.** — •Klaus Molmer |
| SYRA 1.2 | Tue | 11:00–11:30 | V47.01 | **Cooperative non-linear optics using Rydberg atoms** — •Charles Adams |
| SYRA 2.1 | Tue | 14:00–14:30 | V47.01 | **Ultralong-range Rydberg molecules** — •Thomas Pohl |
| SYRA 2.2 | Tue | 14:30–15:00 | V47.01 | **Quantum Information Processing with Rydberg Atoms** — •Philippe Grangier |

## Sessions

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| SYRA 1.1–1.6 | Tue | 10:30–12:30 | V47.01 | **Ultracold Rydberg Atoms and Molecules 1** |
| SYRA 2.1–2.6 | Tue | 14:00–16:00 | V47.01 | **Ultracold Rydberg Atoms and Molecules 2** |
| SYRA 3.1–3.10 | Thu | 10:30–13:00 | V7.03 | **Ultracold Rydberg Atoms and Molecules 3** |

# SYRA 1: Ultracold Rydberg Atoms and Molecules 1

Time: Tuesday 10:30–12:30 Location: V47.01

**Invited Talk** SYRA 1.1 Tue 10:30 V47.01
**Quantum optics and quantum information with Rydberg excited atoms.** — •Klaus Molmer — Aarhus University, Aarhus, Denmark

The significant dipole-dipole interaction between Rydberg excited atoms provides an on/off controllable interaction with promising applications for entanglement operations and quantum computing with neutral atoms. The blockade interaction may be used to carry out quantum gate operations between individually addressed atomic qubits, and in small ensembles, the Rydberg blockade may simultaneously couple all atoms and thus enable quantum control of collective many-body state. On the one hand, this provides new efficient multi-bit schemes for quantum computing and, on the other hand, it gives access to nonclassical states and interaction mechanisms in light-matter interfaces with applications in quantum optics and quantum communication.

**Invited Talk** SYRA 1.2 Tue 11:00 V47.01
**Cooperative non-linear optics using Rydberg atoms** — •Charles Adams — Durham University, Durham, UK

The giant dipole associated with transitions between highly excited Rydberg states can be used to control the optical response of up to 1000 neighbouring atoms. This gives rise to a large cooperative optical non-linearity [1] that is effective at the single photon level providing the basis for fully deterministic all-optical quantum processing. In this talk we will discuss our recent progress in the area of Rydberg non-linear optics and present prospects for future developments.

[1] J. D. Pritchard et al. Phys. Rev. Lett. 105, 193603 (2010).

SYRA 1.3 Tue 11:30 V47.01
**Rydberg electromagnetically induced transparency in dense ultracold gases** — •Christoph S. Hofmann, Georg Günter, Hanna Schempp, Henning Labuhn, Martin Robert-de-Saint-Vincent, Shannon Whitlock, and Matthias Weidemüller — Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg

We report on our latest experimental results on Ryberg electromagnetically induced transparency performed in a regime which is governed by large Rydberg-induced nonlinearities. In these experiments the nonlinear optical response of a strongly interacting Rydberg gas is probed by means of a simple CCD camera. This work is a precursor experiment for realising direct optical images of Rydberg atoms [1]. The experiments are performed in our new apparatus which allows us to realise Bose-Einstein condensates (BECs) of $^{87}$Rb for studies on Rydberg atoms excited from dense atomic gases. Starting with a high flux 2D-MOT, we efficiently load a MOT in order to pre-cool and efficiently transfer atoms into a crossed optical dipole trap. The latter acts as a reservoir that is superimposed with a dimple trap, in which we evaporatively cool the atoms to reach BEC. This simple and robust scheme allows us to perform experiments with short overall cycle times of only $\sim 4.5$ s.

[1] G. Günter et al., arXiv:1106.5443v1 (2011) to be published in PRL

SYRA 1.4 Tue 11:45 V47.01
**Electromagnetically Induced Transparency in Strongly Interacting Rydberg Gases** — •Johannes Otterbach[1], David Petrosyan[2,3], Alexey V. Gorshkov[4], Thomas Pohl[5], Mikhail D. Lukin[1], and Michael Fleischhauer[2] — [1]Physics Department, Harvard University — [2]Fachbereich Physik, TU Kaiserslautern — [3]Institute of Electronic Structure and Laser, FORTH, Crete — [4]Institute for Quantum Information, California Institute of Technology — [5]Max Planck Institute for the Physics of Complex Systems, Dresden

The recent advance in coherently controlling and manipulating strong, long-range Rydberg interactions has triggered various studies of the Rydberg blockade effect for applications in quantum information processing and crystal formation. In this talk I show that Rydberg interactions can be used to alter the photon statistics of a weak probe field after propagating in a coherently prepared atomic Rydberg gas under conditions of Electromagnetically Induced Transparency (EIT). The Rydberg blockade mechanism leads to an effective two-level physics when two photons are separated less than the blockade radius resulting in a strong anti-correlation of two photons separated by an avoided volume. I argue that the formation of such hard-sphere photons is a key-ingredient in the explanation ofthe recent experiment of Pritchard et al. [Phys. Rev. Lett. 105, 193603 (2010)]. Finally the observation of such correlation in future experiments will be discussed.

SYRA 1.5 Tue 12:00 V47.01
**Dipolar Bose-Einstein condensate of Dark-state Polaritons** — •Gor Nikoghosyan[1], Frank E. Zimmer[2], and Martin B. Plenio[1] — [1]Institut für Theoretische Physik, Albert-Einstein Allee 11, Universität Ulm, 89069 Ulm — [2]Max Planck Institute for the Physics of Complex Systems, 01187 Dresden

We put forward and discuss in detail a scheme to achieve BEC of stationary-light dark-state polaritons with dipolar interaction. We extend the works on Bose-Einstein condensation of photons and polaritonic quasiparticles, to the regime of dipolar quantum gases. To this end we introduce a diamond-like coupling scheme in a vapor of Rydberg atoms under the frozen gas approximation. To determine the system*s dynamics we employ normal modes and identify the dark-state polariton corresponding to one of the modes. We show that these polaritonic quasiparticles behave in adiabatic limit like Schrodinger particles with a purely dipolar inter-particle interaction. Moreover, we could show, by analyzing the Bogoliubov spectrum of a homogeneous dipolar BEC, that for a special choice of the dipolar interaction parameter the considered dipolar BEC is, in contrast to usual dipolar BEC, very stable.

SYRA 1.6 Tue 12:15 V47.01
**Rydberg four wave mixing in a thermal gas of Rb** — •Andreas Kölle, Georg Epple, Thomas Baluktsian, Bernhard Huber, Harald Kübler, Robert Löw, and Tilman Pfau — 5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart Gerrmany

The Rydberg blockade effect is a promising candidate for use in quantum devices. In combination with a four wave mixing scheme a single photon source has been proposed. While ultracold gases seem to be the obvious choice, our vision is to use thermal atomic vapor in small glass cells which offers multiple advantages in terms of scalability and ease of use.

We present four wave mixing measurements including a Rydberg state in a thermal vapor cell and compare our results to a single atom model. Furthermore we demonstrate the tunability of the four wave mixing scheme by means of an electric field via the Stark effect on the Rydberg state.

# SYRA 2: Ultracold Rydberg Atoms and Molecules 2

Time: Tuesday 14:00–16:00 Location: V47.01

**Invited Talk** SYRA 2.1 Tue 14:00 V47.01
**Ultralong-range Rydberg molecules** — •Thomas Pohl — MPI for the Physics of Complex Systems, Dresden, Germany

Ultralong-range Rydberg molecules represent an extreme and peculiar example of chemical binding, where a ground state atom is bound inside the electronic wave function of a highly excited Rydberg atom. Owing to their large bond length of several thousand Bohr radii, these molecules - first produced in 2009 [1] - exhibit several unusual properties, some of which will be discussed in this talk.

Following a simplified discussion of the basic interaction mechanisms, I will describe more sophisticated calculations, which reveal, yet, another new binding mechanism based on internal quantum reflection [2]. Good agreement with experiments on ultracold Rubidium molecules, gives strong indication that the predicted molecular states indeed provide a manifestation of such elementary quantum phenomena. A close look at small-electric field effects uncovers the existence of a sizable molecular electric dipole moment [3], which comes as a surprise for homo-nuclear molecules.

Besides being of fundamental interest, such exotic molecules turn out to be also of relevance to other Rydberg-atom settings. In order to illustrate this point, I will consider their collective excitation dynamics in mesoscopic ultracold gases and discuss possible implications for ensemble-based quantum information/optics applications.

[1] V. Bendkowsky et al., Nature (London) **458**, 1005 (2009)
[2] V. Bendkowsky et al., Phys. Rev. Lett. **105**, 163201 (2010)
[3] W. Li et al., Science **334**, 1110 (2011)

**Invited Talk** SYRA 2.2 Tue 14:30 V47.01

**Quantum Information Processing with Rydberg Atoms** — •Philippe Grangier — Institut d'Optique, RD128, 91127 Palaiseau, France

We will present an overview of the use of direct interactions between trapped cold Rydberg states for quantum information processing.

A first approach is to use dipole blockade between individually trapped atoms, used as quantum bits. This allows one to generate entangled pairs of of atomic qubits, and to perform quantum gates, as it has been demonstrated by several recent experiments that will be presented.

A second approach is to use atomic ensembles, and to excite Rydberg polaritons in order to generate "giant" optical non-linear effects, that may lead to quantum gates for photonic qubits. Perspectives in that direction will be also discussed.

SYRA 2.3 Tue 15:00 V47.01

**Electric field impact on ultra-long-range triatomic polar Rydberg molecules** — •Michael Mayle[1], Seth T. Rittenhouse[2], Peter Schmelcher[3], and Hossein R. Sadeghpour[2] — [1]JILA, University of Colorado Boulder and NIST, USA — [2]ITAMP, Harvard-Smithsonian Center for Astrophysics, USA — [3]Zentrum für Optische Quantentechnologien, Universität Hamburg

We explore the impact of external electric fields on a recently predicted species of ultra-long-range molecules that emerge due to the interaction of a ground state polar molecule with a Rydberg atom. The external field mixes the Rydberg electronic states and therefore strongly alters the electric field seen by the polar diatomic molecule due to the Rydberg electron. As a consequence the adiabatic potential energy curves responsible for the binding can be tuned in such a way that an intersection with neighboring curves occurs. The latter leads to an admixture of *s*-wave character to the Rydberg wave function and should significantly facilitate the experimental preparation of this novel species.

SYRA 2.4 Tue 15:15 V47.01

**Supersymmetry in Rydberg-dressed lattice fermions** — •Hendrik Weimer[1], Liza Huijse[1], Alexey Gorshkov[2], Guido Pupillo[3], Peter Zoller[4], Mikhail Lukin[1], and Eugene Demler[1] — [1]Physics Department, Harvard University, Cambridge, MA, USA — [2]IQI, Caltech, Pasadena, CA, USA — [3]University of Strasbourg, Strasbourg, France — [4]University of Innsbruck and IQOQI, Innsbruck, Austria

Supersymmetry is a powerful tool that allows the characterization of strongly correlated many-body systems, in particular in the case of supersymmetric extensions of the fermionic Hubbard model [1]. At the same time, these models can exhibit rich and exotic physics on their own, such as flat bands with a vanishing dispersion relation. We show that such lattice models can be realized with Rydberg-dressed fermions in optical lattices. Strong interactions within the ground state manifold of the atoms can be realized by admixing a weak contribution of a highly excited Rydberg state [2]. We discuss the unique possbilities of ultracold atoms for the detection of supersymmetry and the effects of tuning the system away from the supersymmetric point.

[1] P. Fendley, K. Schoutens, J. de Boer, PRL **90**, 120402 (2003).
[2] J. Honer, H. Weimer, T. Pfau, H. P. Büchler, PRL **105**, 160404 (2010).

SYRA 2.5 Tue 15:30 V47.01

**Aufbau eines Experiments zur Rydberganregung von $^{40}Ca^+$ Ionen** — •Thomas Feldker, Julian Naber, Ferdinand Schmidt-Kaler, Daniel Kolbe, Matthias Stappel und Jochen Walz — Quantum, Institut für Physik, Johannes Gutenberg Universität, Mainz

In Paulfallen gefange, lasergekühlte Ionen gehören zu den vielversprechendsten Kandidaten für die Quanteninformationsverarbeitung, während hoch angeregte Rydbergzustände und die damit verbundene Dipol-Blockade zu den interessantesten Entwicklungen der letzten Jahre in der Atomphysik gehören. Wir vereinen diese Ansätze, indem wir $^{40}Ca^+$ Ionen in einer Paulfalle in Rydbergzustände anregen [1,2]. Ziel ist die Spektroskopie von Rydbergzuständen einzelner Ionen im dynamischen Potential der Paulfalle und die Erzeugung von Vielteilchen-Verschränkung in Ionenkristallen.

Wir fangen und kühlen $^{40}Ca^+$ in einer linearen Paulfalle. Die kalten Ionen sollen in den metastabilen $^3D_{5/2}$ Zustand angeregt werden, aus dem sie mit Laser-Licht bei 123 nm in einen Rydbergzustand angeregt werden können.

[1] F. Schmidt-Kaler, T. Feldker, D. Kolbe, J. Walz, M. Müller, P. Zoller, W. Li and I. Lesanovsky, New J. Phys., 2011 [2] M. Müller, Linmei Liang, Igor Lesanovsky and Peter Zoller, New J. Phys., 2008

SYRA 2.6 Tue 15:45 V47.01

**Strongly interacting single photons in an ultra-cold Rydberg gas** — Stephan Jennewein, Huan Nguyen, Michael Schlagmüller, Christoph Tresp, and •Sebastian Hofferberth — 5. Phys. Institut, Universität Stuttgart

Strong photon-photon coupling can in principle be achieved inside extremely nonlinear media. The search for few-photon nonlinearities is a highly active field, including such diverse systems as quantum dots, NV centers in diamond, atomic ensembles, and single atoms in optical resonators. However, no robust and scalable realization of, for example, a single-photon switch has been achieved so far. Here, we present a new approach that aims to realize dramatically enhanced photon-photon interactions by mapping quantum correlations between strongly interacting atoms inside an ultra-cold gas onto single photons. We show that this technique can be used to implement building blocks for photonic quantum information processing, such as a deterministic single-photon source and a quantum phase gate.

# SYRA 3: Ultracold Rydberg Atoms and Molecules 3

Time: Thursday 10:30–13:00 Location: V7.03

SYRA 3.1 Thu 10:30 V7.03

**Interaction enhanced imaging of individual Rydberg atoms in dense gases** — •Martin Robert-de-Saint-Vincent, Georg Günter, Christoph S. Hofmann, Hanna Schempp, Henning Labuhn, Shannon Whitlock, and Matthias Weidemüller — Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg

Neutral atoms in Rydberg states are highly-polarisable particles, which can experience quantum effects and interactions over macroscopic distances. Many-body systems of Rydberg atoms offer a unique opportunity to create and investigate strong correlations in ultra-cold atomic gases [1]. Until recently, Rydberg ensembles have mostly been studied via field-ionization and subsequent ion detection, typically providing ensemble properties. Here, we present an all-optical method to image individual Rydberg atoms embedded within dense gases of ground state atoms [2]. The scheme exploits interaction-induced shifts on highly polarizable excited states of probe atoms, which can be spatially resolved via an electromagnetically induced transparency resonance. Using a realistic model, we show that individual Rydberg atoms can be imaged with enhanced sensitivity and high resolution despite photon shot noise and atomic density fluctuations. This scheme could be extended to other impurities such as ions, and is ideally suited to studies of spatially-correlated many-body systems.

[1] Pohl et al., PRL 104, 043002 (2010)
[2] G. Günter et al., arXiv:1106.5443v1 (2011), to be published in PRL

SYRA 3.2 Thu 10:45 V7.03

**Rydberg Atom Spectroscopy in Electric Fields** — •Atreju Tauschinsky, Richard Newell, Vanessa Leung, Ben van Linden van den Heuvell, and Robert Spreeuw — Institute of Physics, University of Amsterdam, Amsterdam, Netherlands

We study rubidium Rydberg states in static and oscillating electric fields using Electromagnetically Induced Transparency (EIT) in the 5s-5p-n$\ell$ system for $n \geq 28$ and $\ell = 0 \ldots 2$. We present high-precision Doppler free measurements of DC Stark shifts in a room temperature vapour cell which are in excellent agreement with theoretical calculations. These measurements clearly show that the assumption of quadratically shifting energy levels where the shift is determined by the polarizability of the state is valid only for very small fields, less than 5% of the Inglis-Teller Limit.

We furthermore investigate the behaviour of Rydberg states in superposed AC and DC electric fields and observe populated sidebands of very high order. We present a model, based on generalized Bessel functions for the sideband population induced by oscillating fields in arbitrarily stark-shifting levels and compare the results of this model to our measurements.

Atreju Tauschinsky *et al.* Spatially resolved excitation of Rydberg atoms and surface effects on an atom chip. Phys. Rev. A **81**, 063411 (2010)

C. S. E. van Ditzhuizen *et al.* Observation of Stückelberg oscillations in dipole-dipole interactions. Phys. Rev. A **80**, 063407 (2009)

SYRA 3.3 Thu 11:00 V7.03

**Coherent spectroscopy involving Rydberg states in electrically contacted microcells** — •Renate Daschner, Ralf Ritter, Daniel Barredo, Harald Kübler, Robert Löw, and Tilman Pfau — Universität Stuttgart

Micron sized glass cells filled with atomic vapor are promising candidates for quantum devices based on the Rydberg blockade. Due to the strong interaction between two Rydberg atoms, only one Rydberg excitation is possible within a certain volume characterized by the blockade radius (typically few microns). This effect also provides a nonlinearity that is an essential tool for proposals to entangle mesoscopic ensembles and to realize single photon sources. Measurements show, that coherent Rydberg excitation in thermal vapor and micron-sized cells is possible [1].

The large DC Stark shift of Rydberg atoms provides a possibility to induce transmission or absorption in the medium. To address individual cells one needs electrical contact of the cells. This can be done by coating the inside of glass cells for example with a metal. We show first measurements in coated electrically contacted cells where we can shift the signal by more than one linewidth with a DC electric field.

[1] Kübler, H., Shaffer, J. P., Baluktsian, T., Löw, R. & Pfau, T. Coherent excitation of Rydberg atoms in micrometre-sized atomic vapour cells, Nature Photon. 4, 112-116 (2010)

SYRA 3.4 Thu 11:15 V7.03

**Measurement of the Rydberg ionization current in thermal vapor cells** — •Daniel Barredo, Renate Daschner, Harald Kübler, Ralf Ritter, Robert Löw, and Tilman Pfau — 5. Physikalisches Institut, Universität Stuttgart, Germany

Rydberg atoms confined in atomic vapor cells are promising candidates for the realization of single photon sources and quantum optical devices [1].To date, most information about the behavior of the Rydberg ensembles in thermal vapors has been extracted by absorptive measurements, e.g. EIT. However, to access directly quantities, like the population of the excited states, new methods are needed. In this task, the detection of the Rydberg ionization current provides a complementary and direct insight in the atomic processes.

We show measurements of the Rydberg-ion current in thermal vapor cells equipped with field plates.

[1] Kübler, H., Shaffer, J.P., Baluktsian, T., Löw, R. and Pfau, T. Coherent excitation of Rydberg atoms in micrometre-sized atomic vapour cells, *Nature Photon.* **4**, 112-116 (2010).

SYRA 3.5 Thu 11:30 V7.03

**Scaling laws and correlations in finite Rydberg gases** — •Martin Gärttner[1,2], Thomas Gasenzer[2], and Jörg Evers[1] — [1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg — [2]Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg

We study the coherent dynamics of a finite laser-driven cloud of ultracold Rydberg atoms by calculating the time evolution from the full many body Hamiltonian. Using the frozen gas approximation and treating the atoms as effective two level systems, we are mainly interested in the spatially resolved properties of the gas in its thermalized state. Even for resonant coupling to the Rydberg state, the pair correlation function shows a pronounced structure. It turns out that a simple estimation of the blockade radius predicts the position of the first maximum of the $g^{(2)}$-function quite well. However, we show that algebraic scaling laws as predicted in [1] are modified by finite size effects which serves as a test of the validity of the super atom picture. At positive detuning crystalline structures are observed even without using chirped laser pulses [2], which can be explained by resonant excitation processes and finite size effects.

[1] H. Weimer *et al.*, Phys. Rev. Lett. 101, 250601 (2008)

[2] T. Pohl *et al.*, Phys. Rev. Lett. 104, 043002 (2010)

SYRA 3.6 Thu 11:45 V7.03

**Coherence on Förster resonances between Rydberg atoms** — •Alexander Krupp, Johannes Nipper, Jonathan Balewski, Robert Löw, and Tilman Pfau — 5.Physikalisches Institut, Universität Stuttgart

Förster resonances are non-radiative dipole-dipole interactions between oscillating dipoles. Especially in biochemistry these resonances play a crucial role and describe the energy transfer process between two chromophores, parts of molecules which are responsible for their colors. In our work these resonances occur between a pair of Rydberg atoms, creating strong interactions between the atoms.

We report on studies of Förster resonances between Rydberg atoms in an ultra-cold atomic cloud of $^{87}$Rb. By applying a small electric field we tune dipole coupled pair states into resonance, giving rise to Förster resonances. Via a Ramsey-type atom interferometer we can resolve several resonances at distinct electric field strengths. We study the coherence of the system at and close to the resonances and we observe a change in phase and visibility of the Ramsey fringes on resonance. The individual resonances are expected to exhibit different angular dependencies, opening the possibility to tune not only the interaction strength but also the angular dependence of the pair state potentials by an external electric field. In summary, we now have a tool to coherently tune interactions between Rydberg atoms. In further studies Rydberg atoms could be used as a model system to simulate energy transfer processes in bio-molecules.

SYRA 3.7 Thu 12:00 V7.03

**Collective and quasiparticle excitations in 2D dipolar gases** — •Alexey Filinov und Michael Bonitz — Institut für Theoretische Physik und Astrophysik, Christian-Albrechts-Universität, Leibnizstr. 15, D-24098 Kiel, Germany

The Berezinskii-Kosterlitz-Thouless transition in dipolar atomic, molecular and indirect exciton systems has been recently studied by path integral Monte Carlo simulations [1,2]. Here, we complement these analyses by the spectral densities of the longitudinal collective and single particle (SP) excitations by computing the dynamic structure factor, $S(q, \omega)$, and the SP spectral function, $A(q, \omega)$, across the superfluid to normal fluid transition. The SP spectrum has been worked out by evaluation of the one-particle Matsubara Green's function together with a stochastic optimization method for the reconstruction of $A(q, \omega)$ from imaginary times. We discuss the coupling of both spectra in the *superfluid phase*. We observe sharp resonances due to the quasi-condensate. The excitations in the normal phase are shifted to higher energies and significantly damped beyond the acoustic branch. Our results generalize previous zero-temperature analyses based on variational many-body wavefunctions [2,3]. The underlying physics of excitations and the role of the condensate is not easily extracted from such calculations. Moreover, at finite temperatures the use of the variational approach becomes problematic as the excitation damping becomes significant.

[1] A. Filinov et al., PRL 105, 070401(2010); [2] J. Böning et al., PRB 84, 075130(2011); [3] F. Mazzanti et al., PRL 102, 110405(2009); [4] D. Hufnagl et al., PRL 107, 065303(2011)

SYRA 3.8 Thu 12:15 V7.03

**Crystallization of Rydberg excitations in continuously driven atomic ensembles** — •David Petrosyan[1,2] and Michael Fleischhauer[1] — [1]Fachbereich Physik, Technische Universitaet Kaiserslautern, D-67663 Kaiserslautern — [2]Institute of Electronic Structure and Laser, FORTH, GR-71110 Heraklion, Crete, Greece

We study resonant optical excitations of dense atomic ensembles to the strongly interacting Rydberg states. We show that in the steady state of strong continuous driving the correlations of Rydberg excitation probabilities exhibit damped spatial oscillations reminiscent of the density waves of a finite temperature Luttinger-liquid with Luttinger parameter K << 1/2. For very strong driving, the period of the spatial oscillations saturates to a value corresponding to one collective Rydberg excitation (superatom) per blockade distance. After sudden switching off of the coupling lasers, the Rydberg quasi-crystal can survive for tens or hundreds of microseconds, it can be detected in situ by spatially-resolved Rydberg state ionization or adiabatically converted into a train of single-photon pulses.

SYRA 3.9 Thu 12:30 V7.03

**Nonlocal Nonlinear Optics in cold Rydberg Gases** — •Sevilay Sevinçli[1,2], Nils Henkel[1], Cenap Ates[1], and Thomas Pohl[1] — [1]Max Planck Institute for the Physics of Complex Systems, 01187 Dresden,Germany — [2]Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark

Electromagnetically induced transparency (EIT) provides remarkable possibilities for nonlinear optics by enabling ultraslow group velocities and storage of light. The combination of EIT and interacting Rydberg gases has recently attracted considerable theoretical and experimental interest, as it holds promise for realizing extremely large nonlinearities by exploiting the exaggerated interactions between Rydberg atoms.

We present an analytical theory of the nonlinear response of cold Rydberg gases. This yields simple expressions for the third order susceptibilities which are in excellent agreement with recent measurements. It is further found that the nonlinear susceptibility is not only drastically enhanced but also highly nonlocal in nature, corresponding to long-range photon-photon interactions. Considering the propagation of light in such a Rydberg-EIT medium, this gives rise to a wealth of nonlinear wave phenomena, including soliton formation or modulation instabilities of strongly interacting light fields.

SYRA 3.10 Thu 12:45 V7.03

**Collective interactions in Rydberg-dressed Bose-Einstein condensates** — •Nils Henkel and Thomas Pohl — Max Planck Institute for the Physics of Complex Systems, Dresden

We investigate a Bose-Einstein condensate where atoms are dressed to high Rydberg states with strong van der Waals interactions. Solving exactly the internal many-body state dynamics, we show that this leads to effective ground state interactions with genuine many-body character. In the limit of large laser detunings, two-body interactions dominate [1,2] while many-body interactions become relevant in the strong-driving limit, i.e. in the limit of large laser intensities or weak detunings. We study the effects of these higher order interactions and show that nonlocal phenomena found for binary interactions are still also observable in the presence of strong collective, i.e. genuine many-body, interactions.

[1] N. Henkel, R. Nath and T. Pohl, Phys. Rev. Lett. **104** 195302
[2] F. Maucher et al., Phys. Rev. Lett. **106** 170401