Task-Force Meeting on „Cold Ions and Rydberg Atoms in Atomic Gases“

November, 12th – 13th 2019

Location:

5. Physikalisches Institut
Universität Stuttgart

Room 3.123, Pfaffenwaldring 57

External Guests and Speakers:

Markus Deiss University of Ulm	**Leon Karpa** Universität Freiburg
Johannes Hecker Denschlag University of Ulm	**Thomas Niederprüm** TU Kaiserslautern
Matthew Eiles MPI PKS Dresden	**Herwig Ott** TU Kaiserslautern
Christian Fey MPQ Munich	**Maxim Pyzh** Universität Hamburg
Rene Gerritsma University of Amsterdam	**Hossein Sadeghpour** ITAMP, Harvard University
Henrik Hirzler University of Amsterdam	**Peter Schmelcher** Universität Hamburg
Frederic Hummel Universität Hamburg	**Fabian Thielemann** Universität Freiburg
	Marcel Wagner MPQ Munich

Participants and Speakers from Stuttgart:

Tilman Pfau	**Moritz Berngruber**
Robert Löw	**Christian Hölzl**
Florian Meinert	**Christian Veit**
Felix Engel	**Nicolas Zuber**
Thomas Dieterle	

Programm:

Tuesday, November 12, 2019

10:00 am	Welcome
10:10 am	**Herwig Ott**, *Ultracold Rydberg molecules and heavy Rydberg systems*
10:50 am	**Matthew Eiles**, *Anderson Localization in a Rydberg composite*
11:30 am	*Lunch*
1:10 pm	**Frederic Hummel / Maxim Pyzh**, *Ultra-long-range Rydberg molecules and impurities in ultra-cold quantum gases*
1:50 pm	**Rene Gerritsma**, *The quantum physics of interacting atoms and ions*
2:30 pm	*Coffee & Discussions*
3:00 pm	**Christian Veit**, *An ion microscope to study Rydberg physics and ultracold ions.*
5:00 pm	**Evening Talk: Hossein Sadeghpour**, *0087: The Rydberg Bond!* (room 2.136)
7:00pm	Dinner at "Taverna" (https://www.taverna-stuttgart.de/)

Wednesday, November 13, 2019

9:00 am	**Thomas Dieterle**, *Studying positive and negative ions via Rydberg spectroscopy*
9:40 am	**Christian Fey**, *Triatomic Butterfly Molecules and Rydberg Polarons*
10:20 am	*Coffee & Discussions*
10:50 am	**Leon Karpa**, *Sympathetic cooling of ions in the ultracold regime using bichromatic optical traps*
11:30 am	**Johannes Hecker Denschlag,** *Observation of spin-orbit dependent electron scattering using long-range Rydberg molecules*
12:10 am	*Lunch*

Abstracts:

Johannes Hecker Denschlag (University of Ulm)

Observation of spin-orbit dependent electron scattering using long-range Rydberg molecules

We present experimental evidence for spin-orbit interaction of an electron as it scatters from a neutral atom. The scattering process takes place within a Rb2 ultralong-range Rydberg molecule, consisting of a Rydberg atomic core, a Rydberg electron and a ground state atom. The spin-orbit interaction leads to characteristic level splittings of vibrational molecular lines which we directly observe via photoassociation spectroscopy. We benefit from the fact that molecular states dominated by resonant p-wave interaction are particularly sensitive to the spin-orbit interaction. Our work paves the way for studying novel spin dynamics in ultralong-range Rydberg molecules. Furthermore, it shows that the molecular setup can serve as a micro laboratory to perform precise scattering experiments in the low-energy regime of a few meV.

Thomas Dieterle (University of Stuttgart)

Studying positive and negative ions via Rydberg spectroscopy

The level structure of negative ions near the electron detachment limit dictates the low-energy scattering of an electron with the parent neutral atom. Here, I will present how ultralong-range Rydberg molecules (ULRM) can be used as an atomic-scale system to precisely probe details of the underlying near-threshold anion states [1].

In the second part of this talk, I will focus on immersing a single positive ion into an ultracold gas of atoms employing a tailored photo-ionization scheme. We probe the dynamics of the ion by means of Rydberg blockade [2]. The latter may allow us to investigate ionic transport through quantum degenerate matter in forthcoming experiments.

[1] F. Engel, T. Dieterle, T. Schmid, C. Tomschitz, C. Veit, N. Zuber, R. Löw, T. Pfau, and F. Meinert, Phys. Rev. Lett. 121, 193401 (2018).
[2] F. Engel, T. Dieterle, F. Hummel, C. Fey, P. Schmelcher, R. Löw, T. Pfau, and F. Meinert, Phys. Rev. Lett. 123, 073003 (2019).

Matthew Eiles (MPI PKS Dresden)

Anderson Localization in a Rydberg composite

A Rydberg composite is composed of a Rydberg atom and a structured arrangement of neutral ground state atoms located within the Rydberg electron's wave function. After describing the general properties of this class of systems, focusing in specific on a circular configuration of scatterers, I will discuss possibilities to study Anderson localization in the "thermodynamic limit" of a Rydberg composite. Time permitted, I will examine random Rydberg composites in two and three dimensions and relate our observations there to single-exciton states in an interacting random Rydberg gas.

Christian Fey (MPQ Munich)

Triatomic Butterfly Molecules and Rydberg Polarons

In the first part of this talk I'm going to present an overview on basic properties of triatomic ultralong-range Rydberg molecules in butterfly states. In particular we discuss the structure of electronic and vibrational states and derive effective building principles that explain the resulting molecular geometries.

In the second part we focus on recent progress in modeling spectra and dynamics of Rydberg polaron formation, which is useful for probing interparticle correlations in ultracold atomic gases.

Rene Gerritsma (University of Amsterdam)

The quantum physics of interacting atoms and ions

In recent years, a novel field of physics and chemistry has developed in which trapped ions and ultracold atomic gases are made to interact with each other. These systems find applications in studying quantum chemistry and collisions [1], and a number of quantum applications are envisioned such as ultracold buffergas cooling of the trapped ion quantum computer and quantum simulation of fermion-phonon coupling [2]. In our experiment, we overlap a cloud of ultracold 6Li atoms in a dipole trap with a 171Yb+ ion in a Paul trap. The large mass ratio of this combination allows us to suppress trap-induced heating [3]. For the first time, we buffer gas-cooled a single Yb+ ion to temperatures close to the quantum (or s-wave) limit for 6Li-Yb+ collisions [4]. Before more advanced quantum applications can be considered, it will be of vital importance to be able to control the interactions between the atoms and the ions. To this end, we study interactions between ultracold Rydberg atoms and ions in our Paul trap, thereby merging two of the main atomic physics platforms employed in quantum simulation and computation. We show that the interaction strength between the trapped ions and the atoms can be tuned over a wide range using Rydberg excitation. This could allow for generating spin-spin interactions between the atoms and ions and to build a quantum interface between the two systems [5]. As a first step, we demonstrate Rydberg excitation on a dipole-forbidden transition with the aid of the electric field of a single ion [6,7]. As an alternative to Rydberg excitation (and depending on how long the talk should be), I discuss the prospects for observing atom-ion Feshbach resonances 6Li-Yb+.

[1] M Tomza et al., Rev. Mod. Phys. 91, 035001 (2019).
[2] U. Bissbort et al., Phys. Rev. Lett. 111, 080501 (2013).
[3] M. Cetina et al., Phys. Rev. Lett. 109, 253201 (2012).
[4] T. Felkder et al., arXiv:1907.10926 (2019).
[5] T. Secker et al., Phys. Rev. A 94, 013420 (2016).
[6] T. Secker et al., Phys. Rev. Lett. 118, 263201 (2017).
[7] N. Ewald et al., Phys. Rev. Lett. 122, 253401 (2019).

Leon Karpa (Universität Freiburg)

Sympathetic cooling of ions in the ultracold regime using bichromatic optical traps

Radiofrequency (RF) traps for atomic ions offer a unique level of control accompanied by e.g. long coherence times, excellent state preparation and readout efficiencies and record-worthy qubit gate fidelities. However, in some applications, most notably in investigations of ultracold ion-atom interactions, the presence of RF fields and the resulting driven motion has also been shown to be responsible for undesired or detrimental effects. In the case of ion-atom collisions, they manifest themselves as the so-called micromotion-induced heating [1]. The latter invokes restrictions with respect to the accessible collision energies which so far have been limited to the range of several mK and above for the most available ion-atom combinations [2].

I will discuss an alternative experimental approach to studying ion-atom interactions aiming to combine several key features of ions, foremost their long-range Coulomb interaction, with the versatility of optical traps. This technique known as optical ion trapping allows for confining single ions or ion Coulomb crystals without RF fields [3] and offers comparatively long lifetimes on the order of seconds [4]. I will present our most recent results demonstrating sympathetic cooling of an ion immersed into an ensemble of ultracold atoms overlapped in a set of optical dipole traps [5], and discuss their potential applications in several fields ranging from quantum chemistry to novel quantum simulations.

[1] M. Cetina, A.T. Grier, V. Vuletic, Phys. Rev. Lett. 109, 253201 (2012)
[2] Härter, J.H. Denschlag, Contemp. Phys. 55(1), 33–45 (2014); M. Tomza, K. Jachymski, R. Gerritsma, A. Negretti, T. Calarco, Z. Idziaszek, P.S. Julienne, Rev. Mod. Phys. 91, 035001 (2019)
[3] J. Schmidt, A. Lambrecht, P. Weckesser, M. Debatin, L. Karpa und T. Schaetz, Physical Review X 8, 021028 (2018)
[4] A. Lambrecht, J. Schmidt, P. Weckesser, M. Debatin, L. Karpa and T. Schaetz, Nature Photonics 11, 704 (2017)
[5] J. Schmidt, P. Weckesser, F. Thielemann, T. Schaetz, and L. Karpa, arXiv:1909.08352

Herwig Ott (TU Kaiserslautern)

Ultracold Rydberg molecules and heavy Rydberg systems

I will review our recent activities in Kaiserslautern in the research field of Rydberg molecules and related topics. In particular, I will show that Rydberg molecules can be used to implement an optical Feshbach resonance and that Rydberg molecules can be a promising starting point for the realization of heavy Rydberg systems.

Hossein Sadeghpour (ITAMP, Harvard University)

0087: The Rydberg Bond!

Rydberg atoms provide one of the most exquisite probes to interrogate quantum matter. A curious thing happens when a Rydberg atom becomes neighbor with one, two, three, ... ultracold ground state atom(s). Suddenly ultracold chemistry and many-body quantum physics enter the realm of reality. Much of the work on the realization of such extoic objects was performed in Stuttgart. Here, I will give an update on what has been achieved and perhaps what may lie ahead.

Frederic Hummel / Maxim Pyzh (Universität Hamburg)

In the first part of the talk, we present an overview of investigations on ultra-long-range Rydberg molecules (ULRM) performed in the last years in our group. These exotic molecules consist of one highly excited atom in a Rydberg state and at least one ground-state atom that is trapped and bound at large internuclear distances by low-energy scattering off the Rydberg electron. We focus on three topics: three-atomic ULRM, where a second ground-state atom is bound within the Rydberg-electron orbit, control of molecular alignment by weak external fields, and effects of the spin- and fine-structure interactions that lead to fascinating opportunities to study spin-resolved electron-atom scattering at very low energies.

In the second part of the talk, we give a brief overview on the impurity physics studies in our group, such as a single ion inside a BEC cloud or Bose polarons. They range from the characterization of the static properties of the composite system, over the immersion dynamics and the control of the dynamics by atom-impurity interaction to the formation of mesoscopic molecular structures. Recent experimental progress by Kleinbach et al, where Rydberg states with principal quantum number n=190 are excited such that the Rydberg electron orbits outside the BEC cloud, gives a great opportunity to access so far elusive quantum regime of an atom-ion hybrid system in order to test some of our theoretical predictions and to spur further experimental and theoretical investigations.

Christian Veit (Universität Stuttgart)

An ion microscope to study Rydberg physics and ultracold ions

The development of quantum gas microscopes opened the door to study many-body quantum systems with a resolution on the single atom level. The power of this very successful experimental tool lies in the capability to extract spatial information, enabling the direct study of correlations and transport phenomena.

It is in this spirit that we have designed and built an ion microscope which allows for the spatially and temporally resolved investigation of Rydberg gases and ionic impurities. The microscope features a magnification of more than x1000 and a spatial resolution below 1µm. We present first experimental data of the ion optical system and, as an example, discuss its application in the study of ultracold ion-atom scattering.