



OIST Mini Symposium
Rydberg Atoms for Quantum Technologies
3-5 March 2016, OIST Seaside House, Okinawa, Japan

Programme

3 March, Thursday

8:50 – 9:00	Opening: S. Nic Chormaic (OIST Graduate University, Japan)
9:00 – 10:00	R. Löw (University of Stuttgart, Germany) A Rydberg atom inside a Bose-Einstein Condensate
10:00 – 11:00	K. Ohmori (Institute for Molecular Science, Japan) Direct observation and control of ultrafast many-body electron dynamics in a strongly-correlated ultracold Rydberg gas
11:00 – 11:30	Coffee Break
11:30 – 12:30	M. Safronova (University of Delaware, USA) Rydberg atoms for quantum information and precision measurements
12:30 – 14:30	Discussion and Lunch
14:30 – 15:00	M. Mizoguchi (Institute for Molecular Science, Japan) All-optical generation of a ^{87}Rb Bose-Einstein condensate to be transformed into a defect-free Rydberg crystal in an optical lattice
15:00 – 15:30	S. Machluf (University of Amsterdam, The Netherlands) Adsorbate dynamics on a silica-coated gold surface measured by Rydberg Stark spectroscopy
15:30 – 18:00	OIST campus tour and lab visit
19:00 – 21:00	Working Dinner

4 March, Friday

9:00 – 10:00	A. Browaeys (Institut d'Optique, CNRS, France) Implementation of the quantum Ising model in large arrays of individual Rydberg atoms
10:00 – 11:00	E. Brion (Université Paris-Sud, France) Quantum optical non-linearities induced by Rydberg-Rydberg interactions: a perturbative approach
11:00 – 11:30	Coffee Break
11:30 – 12:30	R. J. C. Spreeuw (University of Amsterdam, The Netherlands) Magnetic microtrap arrays, Rydberg atoms, and quantum simulation
12:30 – 14:30	Discussion and Lunch
14:30 – 15:30	T. Ray (OIST Graduate University, Japan) Rydberg atoms near the surface of optical nanofibers
15:30 – 16:30	P. Windpassinger (Johannes Gutenberg-Universität Mainz, Germany) Towards Rydberg quantum optics in a hollow core fiber
16:30 – 17:00	Coffee Break
17:00 – 18:00	S. Bergamini (The Open University, UK) Rydberg interactions for quantum-enhanced protocols with mixed states
19:00 – 21:00	Working Dinner

5 March, Saturday

9:00 – 10:00	T. C. Killian (Rice University, USA) Ultralong-range Molecules in Strontium Rydberg Gases
10:00 – 11:00	R. González-Férez (Universidad de Granada) Ultralong-range polyatomic Rydberg molecules
11:00 – 11:30	Coffee Break
11:30 – 12:30	K. Nakagawa (University of Electro-Communications, Japan) Towards quantum simulations of many-body systems with cold Rydberg atoms
12:30 – 19:00	Excursion/discussion
19:00 – 21:00	Working Dinner

A Rydberg atom inside a Bose-Einstein Condensate

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The excitation blockade mechanism between interacting Rydberg atoms allows one to place a single Rydberg atom inside a Bose-Einstein condensate. This works even in a situation when the size of the Rydberg atom is much larger than the distance between the ground state atoms in the BEC. As a consequence of this reside many atoms inside the orbit of the wave-function of the Rydberg electron. It has been a surprise that the collisions between the Rydberg electron and the ground state atoms do not directly lead to an ionization process or some other immediate inelastic reaction. As a consequence we are able to observe a coherent interaction between many ground state atoms and a single Rydberg atom in terms of a density dependent line shift and a back-action on the shape of the BEC.

Nevertheless, after some time we do observe inelastic collisions between a neutral ground state atom and the Rydberg atom. The observed time scales, reaction channels and exothermic energy gives insight in a complex reaction dynamics. Some parts of this dynamics are understood by now and gives us a deeper insight in the pair state potentials of a Rydberg atom and a ground state atom.

In the end of the talk I will discuss how this experimental arrangement can be used to image directly the wave-function of a Rydberg atom or how it allows us to study Langevin-type dynamics in the quantum regime.

Direct observation and control of ultrafast many-body electron dynamics in a strongly-correlated ultracold Rydberg gas

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Many-body correlations govern a variety of important quantum phenomena such as the emergence of superconductivity and magnetism in condensed matter. Understanding quantum many-body systems is thus one of the central goals of modern sciences. Here we demonstrate a new pathway towards this goal by generating a strongly-correlated ultracold Rydberg gas with a broadband picosecond laser pulse and by observing its ultrafast many-body electron dynamics directly by time-domain Ramsey interferometry with attosecond precision [1]. Our approach will offer a versatile platform to observe and manipulate nonequilibrium dynamics of strongly-correlated quantum many-body systems on the ultrafast timescale.

[1] N. Takei, C. Sommer, C. Genes, G. Pupillo, H. Goto, K. Koyasu, H. Chiba, M. Weidemüller, and K. Ohmori, arXiv:1504.03635.

Rydberg atoms for quantum information and precision measurements

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Practical implementation of quantum computation requires demonstration of two-qubit quantum gates with very high fidelities. Among the proposals for quantum gates with neutral atoms, Rydberg gate suggested in [1] allows for fast gate operation. The quantum logic operation in Rydberg gate is based on the excitation of atoms to Rydberg states and subsequent blockade of the Rydberg excitations of near-by atoms. Such controlled-NOT quantum gate based on Rydberg blockade interactions between neutral Rb atoms held in optical traps was implemented in [2]. I will review the Rydberg gate schemes and various decoherence processes affecting the gate operation. The issue of the motional heating due to mismatch of the optical trapping potential for the ground and Rydberg state and its solution via the use of the magic wavelengths [3] will be discussed in detail. Magic wavelengths, for which there is no differential ac Stark shift for the ground and excited state of the atom, allow trapping of excited Rydberg atoms without broadening the optical transition. This is an important tool for implementing quantum gates and other quantum information protocols with Rydberg atoms. I will describe the calculation of the magic wavelengths for the 5s-18s transition of rubidium, and benchmark comparison with the corresponding experimental result obtained by measuring the light shift for atoms held in an optical dipole trap at a range of wavelengths near a calculated magic value [4].

In the last part of my talk, I will discuss the applications of Rydberg atoms to precision measurements of Rydberg constant and importance of such measurements for solving the proton radius puzzle [5].

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All-optical generation of a ^{87}Rb Bose-Einstein condensate to be transformed into a defect-free Rydberg crystal in an optical lattice

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Our group at Institute for Molecular Science has realized a strongly-correlated Rydberg gas by an excitation of a disordered ^{87}Rb atomic ensemble in an optical dipole trap using a picosecond pulsed laser and established the method of observing and controlling its ultrafast coherent many-body electron dynamics [1]. As a next step towards a better understanding of strongly-correlated electron systems, we are now introducing an optical lattice to discuss how the homogeneous crystalline structure affects the dynamics when we apply this method to an ordered system having better-defined atomic configurations. In order to obtain a defect-free Rydberg crystal in an optical lattice with one atom per each lattice site, we first need to generate a Bose-Einstein condensate (BEC) with a high phase-space density and then load it into an optical lattice. We will start our presentation by introducing the motivation and framework of our research and mainly talk about the design and construction of our vacuum chamber and the BEC generation by using that apparatus.

It is required that optical accesses for the generation of the BEC and its subsequent loading into an optical lattice as well as the detection of the Rydberg atoms by field ionization should be achieved in one vacuum chamber. It is also needed to suppress collisions with a background gas in the process of evaporative cooling, which leads to the formation of the BEC. Our chamber has a pressure of $\sim 3 \times 10^{-11}$ Torr and thus satisfies these requirements.

The BEC is generated by all-optical means [2] as follows. First, we load the atoms into a standard magneto-optical trap (MOT) from a two-dimensional MOT. Second, we load those atoms into an optical dipole trap formed by three laser beams at a wavelength of 1064 nm crossing on a horizontal plane. Here two beams with the waists of $\sim 100 \mu\text{m}$ crossing at a shallow angle of ~ 7 degree gives a volume to trap atoms as many as possible. Another tightly focused beam with the waist of $\sim 25 \mu\text{m}$ intersects with those two beams at an angle of ~ 60 degree to confine the atoms strongly. Forced evaporation is then performed by ramping down the intensity of those beams gradually for 6 seconds after the atoms are loaded into that dipole trap. We have thus generated the BEC of $\sim 2 \times 10^4$ atoms.

We plan to generate a defect-free Rydberg crystal from this BEC loaded into an optical lattice and excited by a broad-band picosecond laser pulse and to observe its ultrafast coherent many-body electron dynamics by time-domain Ramsey interferometry with attosecond precision [1].

We thank M. Weidemüller and S. Whitlock for fruitful advices. We received generous support from M. Kozuma. This work was partly supported by JST CREST, Grant-in-Aid for Scientific Research by JSPS, and Photon Consortium by MEXT. K.O. thanks Alexander von Humboldt foundation, University of Heidelberg, and University of Strasbourg for supporting this international collaboration.

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Adsorbate dynamics on a silica-coated gold surface measured by Rydberg Stark spectroscopy

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Trapping a Rydberg atom close to a surface is an important step towards the realisation of many proposals for quantum information processing or hybrid quantum systems. One of the challenges in these experiments is posed by the electric field emanating from contaminations on the surface. Here we report on measurements of an electric field created by ^{87}Rb atoms adsorbed on a 25nm thick layer of SiO_2 , covering a 90nm layer of Au. The electric field is measured using a two-photon transition to the $23D_{5/2}$ and $25S_{1/2}$ states. The electric field value that we measure is higher than typical values measured above metal surfaces, but is consistent with a recent measurement above a SiO_2 surface. In addition, we measure the temporal behaviour of the field and observe that we can reduce it in a single experimental cycle, using UV light or by mildly locally heating the surface with one of the excitation lasers, whereas the buildup of the field takes thousands of cycles. We explain these results by a change in the ad-atoms distribution on the surface. These results indicate that the stray electric field can be reduced, such that experiments with trapped Rydberg atoms near surfaces can be performed.

arXiv:1512.07511

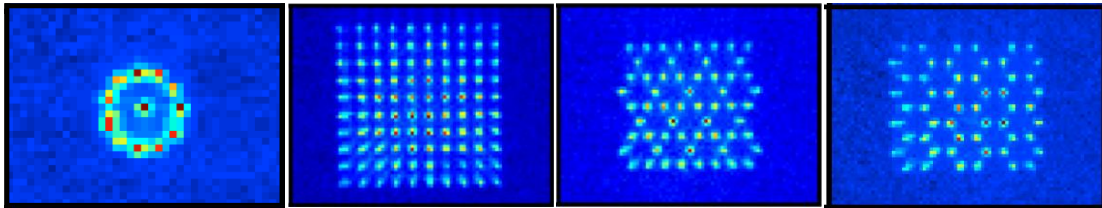
Implementation of the quantum Ising model in large arrays of individual Rydberg atoms

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This talk will present our on-going effort to control the dipole-dipole interaction between cold Rydberg atoms. In our experiment, we trap individual atoms in two-dimensional arrays of optical tweezers [Nogrette, Phys. Rev. X **4**, 021034 (2014)] separated by few micrometers and excite them to Rydberg states using lasers. The arrays are produced by a spatial light modulator, which shapes the dipole trap beam. We can create almost arbitrary geometries of the arrays. The talk will present our measurement of the van der Waals interaction between two individual atoms [Béguin, Phys. Rev. Lett. **110**, 263201 (2013)], as well as the demonstration of the coherent energy exchange between two atoms resulting from their dipole-dipole interaction [Barredo, Phys. Rev. Lett. **114**, 113002 (2015)].

Recently, we have implemented the quantum Ising model in our system [Labuhn, arXiv:1509.04543]. The spin $\frac{1}{2}$ Hamiltonian is mapped onto a system of Rydberg atoms excited by lasers and interacting by the van der Waals Rydberg interaction. We study various configurations such as one-dimensional chains of atoms with periodic boundary conditions, rings, or two-dimensional arrays containing up to 30 atoms. We measure the dynamics of the excitation for various strengths of the interactions between atoms. We compare the data with numerical simulations of this many-body system and found excellent agreement for some of the configurations. This good control of an ensemble of interacting Rydberg atoms thus demonstrates a new promising platform for quantum simulation using neutral atoms.



Fluorescence images of individual atoms trapped in arrays of optical tweezers separated by a few micrometers

Quantum optical non-linearities induced by Rydberg-Rydberg interactions: a perturbative approach

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In this work, we theoretically study the quantum statistical properties of the light transmitted through or reflected from an optical cavity, filled by an atomic medium with strong optical non-linearity induced by Rydberg-Rydberg van der Waals interactions. Atoms are driven on a two-photon transition from their ground state to a Rydberg level via an intermediate state by the combination of a weak signal field and a strong control beam. By using a perturbative approach, we get analytic results which remain valid in the regime of weak feeding fields, even when the intermediate state becomes resonant. Therefore they allow us to investigate quantitatively new features associated with the resonant behavior of the system. We also propose an effective non-linear three-boson model of the system which, in addition to leading to the same analytic results as the original problem, sheds light on the physical processes at work in the system.

Magnetic microtrap arrays, Rydberg atoms, and quantum simulation

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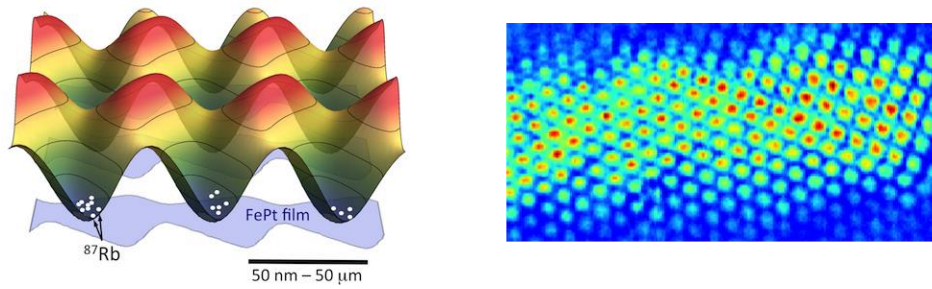
We investigate arrays of magnetic microtraps holding mesoscopic clouds of ultracold ^{87}Rb atoms as a platform for the study of strongly interacting Rydberg atoms. At the heart of our experiment is an atom chip made out of permanently magnetized film, lithographically patterned to create a two-dimensional lattice of Ioffe-Pritchard type magnetic traps [1].

Our atom chip contains lattices with square as well as hexagonal symmetries, presently with a $10\text{ }\mu\text{m}$ 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.

An important challenge in these experiments is posed by the sensitivity of Rydberg atoms to the electric field emanating from ^{87}Rb atoms adsorbed on the chip surface. We measure this field using two-photon spectroscopy of Rydberg levels [3]. We also measure the temporal behaviour of the field and observe that we can reduce it in a single experimental cycle, using UV light or by mildly heating the surface, whereas the buildup of the field takes thousands of cycles. Our results indicate that the stray electric field can be reduced, opening new possibilities for experiments with trapped Rydberg atoms near surfaces.

Excitation of Rydberg atoms in these tight magnetic traps will take 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 wave function.

In addition we are developing lattices with lattice parameter in the $100\text{--}500\text{ nm}$ range. This should yield an implementation of the Hubbard model in novel parameter regimes, with strongly increased energy scales compared to current optical lattices. Our technique based on lithographically patterned magnetic films opens up a vast range of possibilities, in terms of novel geometries and length scales.



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Rydberg atoms near the surface of optical nanofibers

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Optical nanofibres (ONF) are produced by tapering down standard optical fibres to a sub-micron diameter¹. Adiabaticity of the tapering process ensures efficient coupling of light to and from the guided modes in the tapered region to the fiber pigtails. The guided modes of an ONF are tightly confined in the radial direction over a distance much larger than the Rayleigh range. A sub-wavelength diameter ONF also results in a large fraction of the guided mode energy being contained within the evanescent field. The tight confinement of the light provides a high intensity and gradient in the evanescent field even for very small input powers into the fibre pigtails. This feature, in addition to the ease of delivery and collection of light, makes ONFs an attractive choice for probing photon-mediated interactions in an atomic medium.

In our system, we study the interaction of a cold atomic ensemble of rubidium with the evanescent field of an ONF. The spontaneous emission from the atoms can efficiently couple to the guided mode of the ONF making it an attractive tool for detection. The atoms can interact with the evanescent field in two ways. On the one hand, a combination of far red detuned and blue detuned light through the ONF can be used to trap the atoms near its surface². On the other hand, the atoms near the surface can interact with a resonant evanescent field to exhibit ultralow-power nonlinear effects. Here, we shall present our studies on ultralow power frequency up conversion³ and electromagnetically induced transparency⁴ in a multilevel cascaded system of rubidium atoms.

Rydberg atoms have large dipole moments which can interact with a nearby atomic dipole and shift its energy level nonlinearly with the internuclear separation, leading to a blockade of simultaneous excitation. This effect can be used to demonstrate a CNOT gate^{5,6}. We discuss the formation and detection of Rydberg atoms in the vicinity of an ONF. The effect of the van der Waal's force from the surface of the ONF on a single atom and on the collective blockade condition will also be discussed. Finally, we explore the possibility of forming a fibre-coupled CNOT gate and other possible applications of Rydberg atoms near the surface of optical nanofibres.

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Towards Rydberg quantum optics in a hollow core fiber

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Cold atoms inside hollow-core fibers present a promising candidate to study strongly coupled light-matter systems. Adding coherent quantum state control and the intriguing features of Rydberg atoms, i.e. long range dipolar interactions leading to a dipole blockade, to the system should allow for the generation of exotic polaritonic and photonic states.

This talk will review the current status of our experimental setup where laser cooled Rubidium atoms are transported into a hollow-core fiber. We present the first measurements of Rydberg EIT in the optical molasses in front of the fiber and discuss the progress towards Rydberg physics in a quasi-one-dimensional geometry.

Rydberg interactions for quantum-enhanced protocols with mixed states

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Rydberg interactions in ensembles of cold atoms in mixed state can implement a protocol for deterministic quantum computation with one quantum bit (DQC1 [1]). 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, its power scales up with the number of qubits in a mixed state. 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.

We show that the protocol can be operated with many qubits using a cold atoms setting, and we explore the possibility of tackling non-trivial problems [3], such as many-body physics. The same scheme enables the preparation of quantum enhanced probes for phase estimation and promises high-precision measurement, without relying on quantum entanglement and using highly mixed 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. A concrete mixed-state model for quantum metrology is proposed. The scheme can achieve quantum-enhanced precision scaling with the size of the used atomic ensemble [5].

References

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Ultralong-range Molecules in Strontium Rydberg Gases

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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 created and characterized ultralong-range Sr_2 molecules formed from one ground-state $5s^2\ ^1S_0$ atom and one atom in a $5sns\ ^3S_1$ Rydberg state. Molecules are created in a trapped ultracold atomic gas using two-photon excitation, near resonance with the $5s5p\ ^3P_1$ intermediate state. Combined with numerical calculation of the molecular potentials and wavefunctions, this allows us to extract values for the effective s-wave and p-wave scattering lengths describing collisions between an electron and a ground-state Sr atom.

We have also measured the lifetimes of Rydberg atoms and molecules in dense gases of ground state atoms. Results show that, in marked contrast to earlier measurements involving rubidium Rydberg molecules, the lifetimes of the low-lying molecular vibrational states are very similar to those of the parent Rydberg atoms. This reflects the fact that in strontium there is no p-wave resonance for electron scattering in this energy regime, unlike the situation in rubidium. The absence of a resonance offers advantages for experiments involving strontium Rydberg atoms as impurities in quantum gases and for testing theories of molecular formation and decay.

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Ultralong-range polyatomic Rydberg molecules

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Ultralong-range polyatomic Rydberg molecules are formed when a ground-state atom is bound to a Rydberg atom. The binding mechanism of these Rydberg molecules is based on the low-energy collisions between a Rydberg electron and a ground-state atom and leads to the unusual oscillatory behavior of the adiabatic potential energy curves. In the first part of this talk, we will discuss the electronic structure of three different geometries of these Rydberg molecules, including symmetric, asymmetric and planar configurations, and the metamorphosis of the corresponding potential energy surfaces in the presence of an external electric field [1].

If the ground-state atom immersed into the Rydberg wave function is replaced by a heteronuclear diatomic molecule another type of polyatomic Rydberg molecules can form. In this case, the Rydberg electron is coupled to the internal states of the polar ground-state molecule. In the second part of this talk, we will explore the electronic structure and rovibrational properties of these ultralong-range polyatomic Rydberg molecule. For this type of Rydberg molecules, the polar dimer is allowed to rotate in the electric fields generated by the Rydberg electron and Rydberg core as well as an additional external field. We will 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 dimer [2].

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Towards quantum simulations of many-body systems with cold Rydberg atoms

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Recently there has been a considerable interest in using cold Rydberg atoms for quantum information and quantum simulation of many-body quantum systems. Using long-range interaction between Rydberg atoms, one can produce quantum entanglements between atoms separated by more than few micrometers. If we trap cold atoms in optical lattices or micro trap arrays with large spacing, we can realize large size many-body quantum systems with individual atom addressing and high controllability using lasers. Recently several groups have demonstrated quantum simulations using cold Rydberg atoms, and showed the feasibility of these systems for quantum simulations of various quantum spin systems [1,2].

In this talk, we will present about our recent experimental progress towards the realization of quantum simulators using cold Rydberg atoms in optical microtrap arrays. We have developed holographic micro trap arrays for single-atom trapping of Rb atoms in various spatial geometries such as square, triangle and ring lattices. We have realized highly uniform micro trap arrays with up to 100 traps. We will also present our preliminary study about the Rydberg blockade between atoms in a micro optical trap and discuss about the future possible applications of the present Rydberg-atom quantum simulators.

References

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- [2] H. Labuhn, D. Barredo, S. Ravets, S. Leseleuc, T. Macri, T. Lahaye, and A. Bowaeyes, *arXiv:1509.04543*.