Symposium Rydberg Physics in Single-Atom Trap Arrays (SYRY)

jointly organised by
the Quantum Optics and Photonics Division (Q),
the Atomic Physics Division (A), and
the Molecular Physics Division (MO)

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The physics of interacting Rydberg atoms is a very active emerging research field. It not only allows one to study fundamental questions in physics, ranging from molecular physics to strongly-interacting many-body physics, but also provides a versatile platform for quantum technologies, foremost quantum simulation, computation and metrology. This symposium aims to highlight some recent developments in the field, both, on the international and national level. The selection of speakers represents the broad range of topics that emerge from the physics of interacting Rydberg atoms.

Overview of Invited Talks and Sessions

(Lecture hall Audimax)

Invited Talks

SYRY 2.1	Wed	10:30–11:00	Audimax	**Many-body physics with arrays of Rydberg atoms in resonant interaction** — •Antoine Browaeys
SYRY 2.2	Wed	11:00–11:30	Audimax	**Optimization and sampling algorithms with Rydberg atom arrays** — •Hannes Pichler
SYRY 2.3	Wed	11:30–12:00	Audimax	**Slow dynamics due to constraints, classical and quantum** — •Juan P. Garrahan
SYRY 3.3	Wed	14:30–15:00	Audimax	**New frontiers in quantum simulation and computation with neutral atom arrays** — •Giulia Semeghini
SYRY 3.4	Wed	15:00–15:30	Audimax	**New frontiers in atom arrays using alkaline-earth atoms** — •Adam Kaufman
SYRY 3.5	Wed	15:30–16:00	Audimax	**Spin squeezing with finite range spin-exchange interactions** — •Ana Maria Rey

Sessions

SYRY 1.1–1.2	Mon	11:00–13:00	AKjDPG-H17	**Tutorial Rydberg Physics (joint session AKjDPG/SYRY/Q)**
SYRY 2.1–2.5	Wed	10:30–12:30	Audimax	**Rydberg Physics in Single-Atom Trap Arrays 1**
SYRY 3.1–3.5	Wed	14:00–16:00	Audimax	**Rydberg Physics in Single-Atom Trap Arrays 2**

SYRY 1: Tutorial Rydberg Physics (joint session AKjDPG/SYRY/Q)

Time: Monday 11:00–13:00 Location: AKjDPG-H17

Tutorial SYRY 1.1 Mon 11:00 AKjDPG-H17
From the Rydberg Formula to Rydberg arrays — •Jan Michael Rost — Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

Covering milestones in the development of Rydberg physics, the tutorial will introduce the properties of Rydberg atoms and major elements for a theoretical description. Milestones include hydrogen in a magnetic field and doubly excited states of atoms with their connection to classical chaos and periodic orbits through the semiclassical nature of Rydberg electrons. With ultracold environments and traps ultra long-range Rydberg molecules as seeds for Rydberg chemistry have been realized as well as ultracold plasmas. Fundamental phenomena such as the interaction blockade and Rydberg dressing have been identified as major tools to establish and control correlation in Rydberg dynamics on the way to quantum computation with Rydberg arrays which will be the covered in the second tuturial.

Tutorial SYRY 1.2 Mon 12:00 AKjDPG-H17
Quantum simulation and quantum computation with Rydberg atom arrays — •Johannes Zeiher — Max Planck Institute of Quantum Optics, 85748 Garching, Germany — Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

Understanding quantum mechanical systems of many particles at a microscopic level is one of the grand challenges of modern physics. In 1982, Feynman addressed this issue by formulating his vision that one can use well-controlled quantum systems to simulate and understand other quantum systems. Single atoms trapped in individual optical traps coupled to Rydberg states have recently emerged as a versatile experimental platform geared towards realizing Feynman's vision. In this tutorial, I will focus on the basics of this platform. First, I will describe how individual atoms are loaded, detected, and manipulated in optical tweezers. Afterwards, I will explain how strong, switchable interactions between highly excited atomic Rydberg states emerge, and how they can be induced and controlled by lasers. This will set the stage for highlighting the accessible many-body models for quantum simulation and the potential of the platform for quantum computation, followed by a brief discussion of recent experimental breakthroughs in the field.

SYRY 2: Rydberg Physics in Single-Atom Trap Arrays 1

Time: Wednesday 10:30–12:30 Location: Audimax

Invited Talk SYRY 2.1 Wed 10:30 Audimax
Many-body physics with arrays of Rydberg atoms in resonant interaction — •Antoine Browaeys — Institut d'Optique, 2 av Augustin Fresnel, 91120 Palaiseau France

This talk will present our recent work on the quantum simulation of spin Hamiltonians using arrays of Rydberg atoms in resonant, exchange interaction. Combined with a microwave driving between two Rydberg states, we engineer XXZ models with various anisotropies. We illustrate this engineering by studying the dynamics of the system in 2D arrays and in small 1D chain. Recently we have started to explore the possibility of realizing a Dirac spin-liquid on a Kagome lattice. The talk will present the status of this experiment. I will also mention the experimental improvements we performed in the recent years such as the trapping of atoms in a cryogenic environment.

Invited Talk SYRY 2.2 Wed 11:00 Audimax
Optimization and sampling algorithms with Rydberg atom arrays — •Hannes Pichler — Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Innsbruck, Austria — Institute for Theoretical Physics, University of Innsbruck, Austria

Rydberg atom arrays offer novel opportunities to implement quantum information processing protocols. In this talk we discuss a connection between the physics of Rydberg atom arrays and the combinatorial optimization problem of finding large independent sets on a graph. We discuss various implementations of algorithms designed to find the maximum independent set, approximate solutions, and approaches to sample from probability distributions over independent sets, as well as their performance.

Invited Talk SYRY 2.3 Wed 11:30 Audimax
Slow dynamics due to constraints, classical and quantum — •Juan P. Garrahan — University of Nottingham, United Kingdom

Using the East model and the Fredkin spin chain as examples, I will discuss how kinetic constraints give rise to slow, spatially fluctuating relaxation both under classical stochastic or quantum unitary dynamics. I will consider similarities and differences between the classical and quantum cases, and relevant properties such as dynamic heterogeneity and growth of entanglement, singularities in large deviation functions, and the emergence of non-thermal scar-like eigenstates. I will also discuss possible generalisations to higher dimensions.

SYRY 2.4 Wed 12:00 Audimax
Designing complex spin interactions in Rydberg tweezer arrays — •Lea-Marina Steinert[1], Philip Osterholz[1], Robin Eberhard[2], Ludwig Müller[1], Roxana Wedowski[1], Arno Trautmann[1], and Christian Gross[1,2] — [1]Physikalisches Institut, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany — [2]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Synthetic quantum systems based on individually trapped neutral atoms allow studying many-body systems which are hard to solve classically. The classes of many-body systems which can be implemented experimentally are limited by the programmability of the interatomic interactions. We report on the realization of a beyond-Ising spin-1/2 model, where the strong and tunable interactions are based on the off-resonant coupling to highly-excited electronic P states (Rydberg dressing). The effective spins are encoded in the hyperfine ground state manyfold and prepared in individual optical traps (tweezer arrays at various geometries). The Van-der-Waals interactions between the Rydberg states lead to a strong mixing between usually well-separated m_j-sublevels. This opens up controllable interaction channels allowing to implement spin hopping as well as flipping two spins of the same state to the opposite spin state. Using these new types of interactions as well as their long-range character paves the way to implement new types and classes of quantum magnets.

SYRY 2.5 Wed 12:15 Audimax
Rydberg-interacting neutral atoms in a scalable platform of optical tweezers with site-selective addressability — •Dominik Schäffner, Tobias Schreiber, Tilman Preuschoff, Lars Pause, Stephan Amann, Jan Lautenschläger, Malte Schlosser, and Gerhard Birkl — Institut für Angewandte Physik, TU Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt, Germany

In this talk, a versatile platform of optical tweezers is introduced comprising hundreds of focused-beam dipole potentials capable to store laser-cooled atoms with spatial separations in the micrometer regime [1]. Based on micro-fabricated lens arrays, this approach is highly scalable while offering three-dimensional tweezer configurations at no additional cost due to the inherent self-imaging [2]. Site-selective addressability giving precise control over the internal and external atomic degrees of freedom facilitates transport of atoms between sites, coherent coupling of the hyperfine ground states as well as excitation to Rydberg states with individual-atom control [3]. On this basis, defect-free 2D clusters of more than 100 single-atom quantum systems can be created. Furthermore, Rydberg-mediated interactions in assembled atom configurations are demonstrated.

[1] D. Ohl de Mello et. al., Phys. Rev. Lett. **122**, 203601 (2019).
[2] M. Schlosser et. al., arXiv, 1902.05424 (2019).
[3] M. Schlosser et. al., J. Phys. B: At. Mol. Opt. Phys **53** 144001 (2020).

SYRY 3: Rydberg Physics in Single-Atom Trap Arrays 2

Time: Wednesday 14:00–16:00 Location: Audimax

SYRY 3.1 Wed 14:00 Audimax

Optimal quantum gates for a Rydberg atoms quantum computer — •Alice Pagano[1,2,3], Sebastian Weber[1], Hans Peter Büchler[1], and Simone Montangero[2,3] — [1]Institute for Theoretical Physics III, University of Stuttgart, Stuttgart, Germany — [2]Institute for complex quantum systems, University of Ulm, Ulm, Germany — [3]Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova, I-35131 Padova, Italy

Arrays of neutral atoms trapped in optical tweezers are a promising candidate for use in quantum computing. These platforms are highly scalable to large numbers of qubits and neutral atoms boost several attractive features as long coherence times and entanglement via strong dipole-dipole interactions by driving them to highly excited Rydberg states. We aim to realize a Rydberg atom quantum processor with several hundred qubits in the next few years. The smallest building blocks are one and two-qubit quantum gates: to entangle two atoms in the quantum register, a controlled-phase (CZ) gate will be implemented by shining laser pulses onto the two selected atoms. We exploit the Hamiltonian of two atoms to perform a numerical simulation that reproduces the behavior of the CZ gate. We take into account finite temperature, an imperfect Rydberg blockade, and decay out of the Rydberg state as well as a realistic finite raise time for the laser pulses. We compare a protocol with constant pulses obtained via classical optimizers against time-dependent pulses found through the optimal control algorithm dCRAB in an open-loop optimization. The optimal control solution improves the fidelity from 98.65% to 99.90%.

SYRY 3.2 Wed 14:15 Audimax

Time-Optimal Parallel Multiqubit Gates for Rydberg Atoms — •Sven Jandura and Guido Pupillo — Institute de Science et d'Ingénierie Supramoléculaires (ISIS), University of Strasbourg, 67000 Strasbourg, France

Entangling gates between two or more qubits stored in the electronic states of neutral atoms can be implemented via the strong and long-range interaction of atoms in highly excited Rydberg states. Two properties of a gate are particularly desirable: Firstly, the gate should be fast, since many types of error can be mitigated by short gate durations. Secondly, the gate should be parallel, meaning that only global instead of single site addressability with a control laser is needed, thereby simplifying the experimental setup. In this work we use two quantum optimal control techniques, gradient ascent pulse engineering (GRAPE) and Pontryagins's maximum principle, to determine time-optimal parallel laser pulses implementing a controlled-Z(CZ) gate and a three qubit C_2Z gate. Our pulses improve upon the traditional non-parallel pulses for the CZ and the C_2Z gate with just a limited set of variational parameters, demonstrating the potential of quantum optimal control techniques for advancing quantum computing with Rydberg atoms.

Invited Talk SYRY 3.3 Wed 14:30 Audimax

New frontiers in quantum simulation and computation with neutral atom arrays — •Giulia Semeghini — Harvard University

Learning how to create, study, and manipulate highly entangled states of matter is key to understanding exotic phenomena in condensed matter and high energy physics, as well as to the development of useful quantum computers. In this talk, I will discuss recent experiments where we demonstrated the realization of a quantum spin liquid phase using Rydberg atoms on frustrated lattices and a new architecture based on the coherent transport of entangled atoms through a 2D array. Combining these results with novel technical tools on atom array platforms could open a broad range of possibilities for the exploration of entangled matter, with powerful applications in quantum simulation and information.

Invited Talk SYRY 3.4 Wed 15:00 Audimax

New frontiers in atom arrays using alkaline-earth atoms — •Adam Kaufman — JILA/University of Colorado Boulder, Boulder, USA

Quantum science with neutral atoms has seen great advances in the past two decades. Many of these advances follow from the development of new techniques for cooling, trapping, and controlling atomic samples. As one example, the technique of optical tweezer trapping of neutral atom arrays has been a powerful tool for quantum simulation and quantum information, because it enables scalable control and detection of individual atoms with switchable interactions. In this talk, I will describe ongoing work at JILA where we have explored a new type of atom - two-electron atoms - for optical tweezer trapping. While their increased complexity leads to challenges, these atoms also offer new scientific opportunities by virtue of their rich internal degrees of freedom. Accordingly, they have impacted multiple areas in quantum science, ranging from quantum information processing to quantum metrology. I will report on my group's progress in these areas.

Invited Talk SYRY 3.5 Wed 15:30 Audimax

Spin squeezing with finite range spin-exchange interactions — •Ana Maria Rey — JILA, NIST and University of Colorado at Boulder

Squeezed states represent one class of entangled states which are important in quantum sensing and metrology. Typically, squeezed states are be realized via collective all-to-all interactions. However, in many quantum systems the only accessible interactions have a finite range, prohibiting the realization of such collective models. In this talk I will report how the XXZ spin model with interactions that fall off with distance r as $1/r^\alpha$ in D=2 and 3 spatial dimensions or XX spin models with soft-core interactions can realize spin squeezing comparable to the infinite-range $\alpha = 0$ model in a broad range of parameter regimes. In particular, I will discuss the application of these ideas to the case of weakly-dressed Rydberg atoms where an external drive can be used to engineer XX soft-core interactions and in turn to generate large levels of spin squeezing even in the presence of experimentally unavoidable decoherence sources.