"Applications of Ultracold Rydberg Gases"

792. WE-Heraeus-Seminar

23 – 28 July 2023

at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 792. WE-Heraeus-Seminar:

Rydberg atoms in ultracold quantum gases offer various applications reaching from quantum optics through quantum simulation all the way to quantum computing. The large success of this platform is rooted in the near-perfect isolation of ultracold quantum gases from the environment, which enables excellent control and detection at the single-atom level.

The strong interactions between Rydberg atoms take a central role in the field and the various emerging applications. In quantum simulations, recent breakthroughs in the control of individual atoms have allowed for simulating quantum spin models of several hundred spins, beyond the realm that can be simulated exactly on classical machines. A new frontier has recently emerged from these experiments in the quest to realize digital quantum computers. For quantum optics applications, Rydberg excitations have been used to switch the optical response of atomic ensembles at the single-photon level. Binding Rydberg atoms in long-range molecules allows for the creation of novel molecular bound states, where quantum control facilitates near-perfect manipulation of all quantum degrees of freedom. Finally, a range of novel directions have emerged in the recent past, including the development of cryogenic experimental setups that promise to open the path towards better isolation of quantum simulators or novel quantum simulation platforms such as circular Rydberg states.

This workshop aims to bring together the world-leading researchers in different areas of Rydberg physics, with the goal to foster exchange and continue the strong sense of community in the field. The span of topics is intentionally kept broad to bring together experts in various fields and enable to open new frontiers in ultracold Rydberg systems.

Scientific Organizers:

Dr. Johannes Zeiher, Max-Planck-Institut für Quantenoptik, Garching /DE
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Introduction

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Registration:

Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, Reception Office
Sunday (17:00 h - 21:00 hrs) and Monday morning

Program

Program *(CEST)*

Sunday, 23 July 2023

17:00 – 21:00	ARRIVAL and REGISTRATION	
18:30	*BUFFET SUPPER*	

Monday, 24 July 2023

07:30	*BREAKFAST*	

Quantum Optics
Session chair: Florian Meinert

08:45 – 09:45	Nina Stiesdal	**Waveguide QED with Rydberg Superatoms**
09:45 – 10:30	Pascal Weckesser	**Controlling a Subwavelength Atomic Mirror Using a Single Rydberg Atom**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Sven Jandura	**Novel Two- and Multi-Qubit Entangling Gates on Rydberg Atoms**
11:45 – 12:30	Stephan Dürr	**Quantum-logic Gate between Two Optical Photons with an Average Efficiency above 40%**
12:30– 12:45	**Conference Photo (outside at the main entrance)**	
12:45 – 14:00	*LUNCH BREAK*	

Session chair: Matthew Eiles

14:00 – 14:45	Alex Guttridge	**Observation of Rydberg Blockade Due to the Charge-dipole Interaction Between an Atom and a Polar Molecule**

Program *(CEST)*

14:45 – 15:30	Thomas Pohl	**Collective Light-Matter Interactions in Ultracold Rydberg Ensembles**
15:30 – 16:15	Dylan Brown	**Rydberg Excitation and Casimir-Polder Interaction of 87Rb Atoms Mediated by an Optical Nanofiber**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 17:30	Wenchao Xu	**Atomic Ensembles Meet Qubits**
17:30 – 17:45	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
17:45 – 18:30	**Flash Presentations**	
18:30	*DINNER*	

Program *(CEST)*

Tuesday, 25 July 2023

07:30	*BREAKFAST*	

Quantum Simulation
Session chair: Thomas Pohl

08:45 – 09:45	Antoine Browaeys	**Magnetism and Spin Squeezing with Arrays of Rydberg Atoms**
09:45 – 10:30	Giulia Semeghini	**Towards New Frontiers of Quantum Science with Dual-species Atom Arrays**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Malte Schlosser	**Scalable Architecture of Assembled Single-Atom Qubit Arrays in Two and Three Dimensions**
11:45 – 12:30	Lea-Marina Steinert	**Designing Tunable Spin Interactions in Rydberg Tweezer Arrays**
12:30 – 14:00	*LUNCH BREAK*	

Session chair: Antoine Browaeys

14:00 – 14:45	Hans Peter Büchler	**Functional Completeness of Planar Rydberg Structures**
14:45 – 15:30	Hannes Pichler	**Universal Quantum Computation with Globally Driven Rydberg Atom Arrays**
15:30 – 16:15	Sebastian Weber	**QRydDemo - Quantum Computing with Rydberg Atoms**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 18:30	**Poster Session 1**	
18:30 – 19:30	*DINNER*	
19:30	**Discussion**	

Program *(CEST)*

Wednesday, 26 July 2023

07:30	*BREAKFAST*	

Quantum Computing
Session chair: Hans Peter Büchler

08:45 – 09:45	Adam Kaufman	**Microscopically-controlled Arrays of Alkaline-earth Atoms**
09:45 – 10:30	Jonathan Pritchard	**Scalable Qubit Arrays for Quantum Computation and Optimisation**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Markus Saffman	**Circuit Model Quantum Computing with Neutral Atom Arrays**
11:45 – 12:30	Alexander Lukin	**Quench Dynamics as a Shortcut to Adiabaticity in Rydberg Atoms Arrays**
12:30 – 14:00	*LUNCH BREAK*	

Session chair: Adam Kaufman

14:00 – 14:45	Loïc Henriet	**Quantum Feature Maps for Graph Machine Learning on a Neutral Atom Quantum Processor**
14:45 – 15:30	Sebastian Blatt	**Neutral-Atom Quantum Computing in the Munich Quantum Valley**
15:30 – 16:15	Ben Bloom	**Building Utility-Scale Machines with AE-Qubits**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 18:30	**Time for Excursion**	

18:30	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, with complimentary drinks)*

Program *(CEST)*

Thursday, 27 July 2023

07:30	*BREAKFAST*	

Emerging Platforms
Session chair: Giulia Semeghini

08:45 – 09:45	Tilman Pfau	**A Molecular Bond Between Ions and Rydberg Atoms**
09:45 – 10:30	Markus Hennrich	**Speeding up Trapped Ion Quantum Processors via Rydberg Interaction**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Daniel Grün	**Quantum Simulation with Rydberg States of Erbium**
11:45 – 12:30	Jeff Thompson	**Quantum Computing with Yb Rydberg Atoms**
12:30 – 14:00	*LUNCH BREAK*	

Session chair: Sebastian Hofferberth

14:00 – 14:45	Sylvain de Léséleuc	**Ultrafast Rydberg Experiments with Ultracold Atoms in Arrays of Optical Tweezers**
14:45 – 15:30	Jacob Hines	**Spin Squeezing by Rydberg Dressing in an Array of Atomic Ensembles**
15:30 – 16:15	Anna Dawid	**Towards Learning Interactions Between Rydberg Atoms from Experimental Snapshots**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 18:30	**Poster Session 2**	
18:30 – 19:30	*DINNER*	
19:30	**Discussion**	

Program *(CEST)*

Friday, 28 July 2023

07:30	*BREAKFAST*	

Rydberg Molecules
Session chair: Johannes Zeiher

08:45 – 09:45	Sébastien Gleyzes	**Circular Rydberg Atoms of Strontium**
09:45 – 10:30	Thomas Niederprüm	**The many Faces of Ultracold Rydberg Interaction**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Andreas Kruckenhauser	**High-dimensional SO(4)-Symmetric Rydberg Manifolds for Quantum Simulation**
11:45 – 12:30	Matthew Eiles	**Rydberg Molecules, Composites, and Polarons**
12:30 – 12:45	**Closing Remarks and Poster Prizes**	
12:45	*LUNCH*	

End of Seminar / Departure

Posters

Poster List

Neethu Abraham	**Non-adiabatic Decay Rates of Charged Rydberg Molecules**
Maximilian Ammenwerth	**Individual Strontium Atoms in a Hybrid Lattice-tweezer Quantum Simulator**
Jana Bender	**Phase Transitions in Self-organized Rydberg Facilitation Dynamics**
Julia Bergmann	**Engineering Lattice Gauge Theories with a Rydberg Atom Processor**
Gerhard Birkl	**Microlens-based Tweezer Arrays for Rydberg-interacting Atoms**
Sebastian Borówka	**Converting Microwave Photons to Infrared via Room-temperature Rydberg Atomic Vapours**
Daniel Bosworth	**Charged Ultralong-range Rydberg Trimers**
Eduard Jürgen Braun	**Out-of-equilibrium Physics in a Disordered Dipolar Heisenberg Quantum Spin System**
Giacomo Cappellini	**A New Machine with Programmable Arrays of Rydberg Ytterbium Atoms for Quantum Computing Applications**
Ying-Cheng Chen	**Generation of Two-dimensional Bottle Beam Arrays of Arbitrary Geometries for Atom Trapping with a Spatial Light Modulator**
Marco Di Liberto	**High-dimensional SO(4)-Symmetric Rydberg Manifolds for Quantum Simulation**
Julian Fiedler	**Probing Dense Rydberg Gases Excited by Ultrashort Laser Pulses**

Poster List

Vladislav Gavryusev	**Programmable Quantum Simulator with Strontium Rydberg Atoms in Optical Tweezer Arrays**
Katja Gosar	**EIT-based Detection of Rydberg Atoms for Quantum Simulation with Cesium Atomic Ensembles**
Santiago Higuera Quintero	**Experimental Validation of the Kibble-Zurek Mechanism on a Digital Quantum Computer**
Lukas Homeier	**Realistic Scheme for Quantum Simulation of Z2 Lattice Gauge Theories with Dynamical Matter in (2+1)D**
Niels Kjaergaard	**THz Polarization Spectroscopy of Rubidium Rydberg Atoms**
Lucas Leclerc	**Quantum Graph Machine Learning on a Rydberg Atom Processor**
Takuya Matsubara	**Sub-nanosecond Laser Excitation of Ultracold Atoms: Towards Ultrafast Quantum Computers and Super-radiance Studies**
Madhav Mohan	**Robust Control and Optimal Rydberg States for Neutral Atom Two Qubit Gates**
Manuel Morgado	**Control System and Architecture for a Rydberg Quantum Processor**
Rick Mukherjee	**Rydberg Simulator: From QCD to Random Ensemble States**
Maximilian Müllenbach	**Characterizing Operator Growth in Disordered Quantum Spin Systems via Out-of-Time-Ordered Correlators**

Poster List

Baptiste Muraz	**Quantum Simulation with Circular States of Strontium**
Thilina Muthu-arachchige	**Rydberg Quantum Optics in Ultracold Ytterbium Gases**
Kristian Knakkergaard Nielsen	**Exact Two-body Bound States and Dynamics of Dopants in Ising Antiferromagnets**
Boyko Nikolov	**Analogue Quantum Computing and Blue-Detuned Bottle Traps in Caesium Rydberg Atom Arrays**
Alice Pagano	**Optimal Control for Rydberg Atom Quantum Computation**
Michael Peper	**Precision Spectroscopy and Modeling of Yb Rydberg States for Neutral Atom Quantum Computing**
Ana Pérez Barrera	**A New Strontium Quantum Simulator Using Arrays of Rydberg Atoms for Simulating Lattice Gauge Theories**
Nejira Pintul	**Quantum Computation with Neutral Alkaline-Earth-like Ytterbium Rydberg Atoms in Optical Tweezer Arrays**
Lode Pollet	**Magnetism in the Two-dimensional Dipolar XY Model**
Ankul Prajapati	**Towards Realization of Long-lived Chains of Circular Rydberg Atoms for Quantum Simulation**
Nora Reinić	**Tree Tensor Networks for Quantum Many-body Systems at Finite Temperatures**

Poster List

Achim Scholz	**QRydDemo - A Rydberg Atom Quantum Computer Demonstrator**
Rohan Srikumar	**Nonadiabatic Interaction Effects in the Spectra of Ultralong-range Rydberg Molecules**
Xintong Su	**Cryogenic Strontium Quantum Processor**
Poetri Sonya Tarabunga	**Chiral Spin Liquids in Rydberg Models with Dipolar Exchange Interactions**
Yu Chih Tseng	**Rydberg Atom Array for Simulating Spin Systems**
Rik van Herk	**Strontium Atoms in Tweezer Arrays for Hybrid Quantum Computing**
Agata Wojciechowska	**Mercury Rydberg Molecules**
Fan Yang	**Probing Hilbert Space Fragmentation and Time Crystalline Order with Rydberg Atoms**
Zhongda Zeng	**Quantum Annealing for Quantum Optimization Problems with Arbitrary Connections in Rydberg Atom Arrays**
Zhao Zhang	**Neutral-Atom Quantum Computing Demonstrator**

Abstracts of Lectures

(in alphabetical order)

Neutral-Atom Quantum Computing in the Munich Quantum Valley

S. Blatt[1,2,3]

[1]Ludwig-Maximilians-Universität München, Germany
[2]Max-Planck-Institut für Quantenoptik, Garching, Germany
[3]planqc, Garching, Germany

I report on the progress towards neutral-atom quantum computing demonstrators in the Munich Quantum Valley. These demonstrators will be based on ultracold strontium atoms trapped in optical tweezer arrays and optical lattices. Qubits in alkaline-earth atoms such as strontium can be realized in the nuclear spin, on the clock transition between the ground state $^1S_0$ and the lowest metastable triplet state $^3P_0$, or between the metastable triplet states $^3P_0$ and $^3P_2$. Two-qubit gates can be realized by single-photon transitions from one of the triplet states. Dedicated experiments are being built for each of these possibilities to identify the most suitable candidate for quantum computing prototypes that will be commercially available through the newly founded startup planqc.

In parallel to these efforts, atomic quantum technologies are continuously developed in Munich. Here, I report on recent progress on closing the third leg of the $^1S_0$ – $^3P_0$ – $^3P_2$ state triangle by coherently driving the magnetic quadrupole transition between $^1S_0$ and $^3P_2$ ($m = 0$). We find that high-precision spectroscopy on this transition can be made to work reliably at many wavelengths by polarizability engineering. These developments open the way to create well-controlled "optical qutrits" in a magic-wavelength optical trap.

Building Utility-Scale Machines with AE-Qubits

Benjamin Bloom and Atom Computing Staff[1,2]
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Alkaline-Earth based-qubits have long been theorized to have exceptional properties including exquisite coherence and multiple long lived states useful for coherent manipulation of both nuclear- and electronic-degrees of freedom [1]. Atom Computing, a US-based-startup, is building ever larger and more performant systems with the end goal of building a useful quantum computer. In this talk I will go over our two most recent publications [2, 3] covering various aspects of SPAM, 1Q gates, and MCM. In addition I will give an overview of 2Q gates with nuclear spin qubits as well as showcase some of the capabilities of our next generation systems which aim to solve some of the inherent, neutral-atom-specific-challenges in building a useful quantum computer.

References

[1] Daley, A. J. *et al.*, *PRL* **101**, 170504, (2008)
[2] Barnes, K. *et al. Nat Commun* **13**, 2779 (2022).
[3] TBA-Spring-2023

Magnetism and spin squeezing with arrays of Rydberg atoms

Antoine Browaeys

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This talk will present our recent work on the use of arrays of up to 100 Rydberg atoms to study quantum magnetism and to generate entangled states useful for quantum metrology. By exciting the atoms into Rydberg states, we make them interact by the resonant dipole interaction. The system thus implements the XY spin ½ model, which exhibits various magnetic orders depending on the ferromagnetic or antiferromagnetic nature of the interaction. In particular, we adiabatically prepare long-range ferromagnetic order. When the system is placed out of equilibrium, the interactions generate spin squeezing. We characterize the degree of squeezing and observe that it scales with the number of atoms. We also use this quench method to extract the dispersion relation of the XY model, both in the ferro and antiferromagnetic case.

Rydberg excitation and Casimir-Polder interaction of 87Rb atoms mediated by an optical nanofiber.

Alexey Vylegzhanin,[1] Dylan J. Brown,[1] Aswathy Raj,[1] Danil F. Kornovan,[2] Jesse L. Everett,[1] Etienne Brion,[3] Jacques Robert,[4] and Síle Nic Chormaic[1]

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[3]Laboratoire Collisions Agr´egats R´eactivit´e, UMR5589, Universit´e Toulouse III Paul Sabatier, CNRS, F-31062 Toulouse Cedex 09, France.
[4]Universit´e Paris-Saclay, CNRS, Laboratoire de Physique des Gaz et des Plasmas, 91405 Orsay, France.

Cold Rydberg atoms are a promising platform for quantum technologies [1] and combining them with optical nanofibers [2] has the potential to create robust quantum information devices. We experimentally observe the excitation of cold rubidium atoms to a large range of Rydberg S and D states through interaction with the evanescent field of an optical nanofiber. We develop a theoretical model to account for experimental phenomena present such as the AC Stark shifts and the Casimir-Polder interaction [3]. This work strengthens the knowledge of Rydberg atom interactions with optical nanofibers and is a critical step toward the implementation of all-fiber quantum networks and waveguide QED systems using highly excited atoms.

References

[1] M. Saffman, T. G. Walker, and K. Mølmer, Quantum information with Rydberg atoms, Rev. Mod. Phys. **82**, 2313 (2010)

[2] T. Nieddu, V. Gokhroo, and S. Nic Chormaic, Optical nanofibres and neutral atoms, Journal of Optics **18**, 053001 (2016)

[3] F. Le Kien, D. F. Kornovan, S. Nic Chormaic, and T. Busch, Repulsive Casimir-Polder potentials of low-lying excited states of a multilevel alkali-metal atom near an optical nanofiber, Phys. Rev. A **105**, 042817 (2022).

Functional completeness of planar Rydberg structures

Simon Stastny, Hans Peter Büchler, Nicolai Lang

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The construction of Hilbert spaces that are characterized by local constraints as the low-energy sectors of microscopic models is an important step towards the realization of a wide range of quantum phases with long-range entanglement and emergent gauge fields. Here we show that planar structures of trapped atoms in the Rydberg blockade regime are functionally complete: Their ground state manifold can realize any Hilbert space that can be characterized by local constraints in the product basis. We introduce a versatile framework, together with a set of provably minimal logic primitives as building blocks, to implement these constraints. As examples, we present lattice realizations of the string-net Hilbert spaces that underlie the surface code and the Fibonacci anyon model. We discuss possible optimizations of planar Rydberg structures to increase their geometrical robustness.

Towards learning interactions between Rydberg atoms from experimental snapshots

A. Dawid[1], A. Sengupta[1,2,3] and A. Georges[1,4,5,6]

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[6] *DQMP, Université de Genève, 24 quai Ernest Ansermet, CH-1211 Genève, Switzerland*

Quantum simulators promise solving problems that are not accessible to classical computers, such as quantum many-body problems with many degrees of freedom and large-scale entanglement. To achieve this goal, quantum simulators need to be fully controllable and efficiently validated. In particular, inferring the experimentally realized Hamiltonian through a scalable number of measurements constitutes the challenging task of Hamiltonian learning, which is especially important in presence of experimental noise like disordered positions of optical tweezers. In this work, we present a scalable approach to Hamiltonian learning with graph neural networks (GNNs). Using numerically simulated snapshots of a quantum system across its time evolution as input data, we infer the underlying interactions between the spins on an example of the 3x3 transverse-field Ising model. The input-size invariance of GNNs should allow training them on numerically simulated data and applying to larger-scale experimental snapshots, e.g., to infer the disordered interactions between Rydberg atoms in optical tweezers.

Ultrafast Rydberg experiments with ultracold atoms in optical tweezers

Sylvain de Léséleuc[1], **Y. Chew, T. Tomita, T.P. Mahesh, S. Sugawa, K. Ohmori**

[1]*Institute for Molecular Science, National Institutes of Natural Sciences, Okazaki Japan*

Rydberg atoms, with their giant electronic orbitals, exhibit dipole-dipole interaction reaching the GHz range at a distance of a micron (C_3 ~ GHz.μm^3), making them a prominent contender for **realizing ultrafast quantum operations**. However, such strong interactions have never been harnessed so far because of the stringent requirements on the fluctuation of the atom positions and the necessary excitation strength. Here, we **introduce novel techniques to enter this regime and explore it** with two strongly-interacting single atoms [1].

First, we trap ^{87}Rb atoms in **holographic tweezers** focused with a high-NA lens (0.75), allowing to **bring two atoms at distance as close as 1.2 μm**. The atoms are then cooled to the **motional ground-state** of the tweezers and thus localized with a quantum-limited precision of 30 nm, which allows to **unlock coherent ultrastrong interaction**. Then, we use **ultrashort, picosecond, laser pulses to excite** a pair of these close-by atoms to a Rydberg state simultaneously [2], far beyond the Rydberg blockade regime.

Following excitation, atoms experience the dipole-dipole interaction, which, for our particular choice of Rydberg state, gives rise to an **energy exchange** between the two atoms [3]. We observe this **coherent dynamic occurring on the nano-second timescale**. After a full exchange, the atoms are back in their initial orbitals with a π-phase shift. We measured this phase shift by probing the superposition of a ground and Rydberg orbital by Ramsey interferometry with attosecond precision. This phase shift is the key to the realization of an ultrafast two-qubit C-Z gate. The techniques demonstrated here **opens the path for ultrafast quantum simulation and computation operating at the speed-limit set by dipole-dipole interactions.**

References

[1] Y. Chew et al., “Ultrafast energy exchange between two single Rydberg atoms on a nanosecond timescale”, Nat. Photonics **16**, 724 (2022).
[2] Mizoguchi et al., “Ultrafast creation of overlapping Rydberg electrons in an atomic BEC and Mott-insulator lattice”, Phys. Rev. Lett. **124**, 253201 (2020).
[3] Ravets, S. et al. “Coherent dipole–dipole coupling between two single Rydberg atoms at an electrically-tuned Förster resonance”, Nat. Physics **10**, 914 (2014).

Quantum-logic gate between two optical photons with an average efficiency above 40%

Thomas Stolz, Hendrik Hegels, Maximilian Winter, Bianca Röhr, Ya-Fen Hsiao, Lukas Husel, Gerhard Rempe, and Stephan Dürr

Max Planck Institute of Quantum Optics, Garching, Germany

Optical qubits uniquely combine information transfer in optical fibers with a good processing capability and are therefore attractive tools for quantum technologies. A large challenge, however, is to overcome the low efficiency of two-qubit logic gates. The experimentally achieved efficiency in an optical controlled NOT (CNOT) gate reached approximately 11% in 2003 and has seen no increase since. Here we report on a new platform that was designed to surpass this long-standing record. The new scheme avoids inherently probabilistic protocols and, instead, combines aspects of two established quantum nonlinear systems: atom-cavity systems and Rydberg electromagnetically induced transparency. We demonstrate a CNOT gate between two optical photons with an average efficiency of 41.7(5)% at a postselected process fidelity of 81(2)% [1]. Moreover, we extend the scheme to a CNOT gate with multiple target qubits and produce entangled states of presently up to five photons. All these achievements are promising and have the potential to advance optical quantum information processing in which almost all advanced protocols would profit from high-efficiency logic gates.

References

[1] T. Stolz et al. Phys. Rev. X **12**, 021035 (2022).

Rydberg molecules, composites, and polarons

M. Eiles[1]

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When a Rydberg atom and a ground state “perturber” atom encounter one another in an ultracold gas, the long-range interaction between them is mediated by the scattering of the Rydberg electron off of the perturber. The antinodes of the Rydberg wave function form potential wells in which the perturber can be trapped, binding the two atoms together into a molecule. This unusual interaction mechanism is also capable of binding several atoms together into trimers, tetramers, and so on.

As the number of ground state atoms increases, a description of this system within the framework of molecular physics becomes impractical [1,2]. In this talk, I will use several concepts from solid-state physics to describe a Rydberg atom immersed in a dense environment of ground state atoms. First, I will investigate how a structured environment of immobile perturbers modifies the spectrum of the Rydberg electron, which is highly degenerate in the absence of perturbers due to the SO(4) symmetry of the excited atom. I will show that this degeneracy leads to an exact mapping between the perturbed electronic states and the states of a particle in a tight-binding lattice, where the confluence of the long-ranged Coulomb potential and the short-ranged electron-atom potentials leads to a plethora of possible lattice parameters [3]. With this mapping, I will show how to realize different topological models and demonstrate the localization of the Rydberg electron in a disordered lattice.

In the second case, I will focus on a very different regime where the Rydberg electronic state is independent of the number and positions of the perturbers, which are now treated fully quantum mechanically. Such a system is an exotic realization of a quantum impurity problem typified by the Bose polaron studied in ultracold gases. We use a bosonic functional determinant approach to obtain the full many-body absorption spectrum out of the two-body physics of the impurity-atom [2]. I will explore the similarities and differences between this system and other impurity problems of recent theoretical and experimental interest, and use these comparisons to draw general conclusions about quantum impurities.

References

[1] A. L. Hunter, M. T. Eiles, A. Eisfeld, and J. M. Rost Phys. Rev. X **10**, 031046 (2020)

[2] R. Schmidt, H. R. Sadeghpour, and E. Demler, Phys. Rev. Lett **116**, 105302 (2016)

[3] M. T. Eiles, A. Eisfeld, and J. M. Rost arXiv: 2111.10345 (2021)

Circular Rydberg Atoms of Strontium

L. Lachaud[1], B. Muraz[1], J.M. Raimond [1], M. Brune[1], and S. Gleyzes[1]

[1] *LKB, Collège de France, CNRS, ENS-Université PSL, SU, Paris, France.*

Rydberg atoms arrays are one of the most promising platforms for quantum simulation. Alkali ground-state atoms, trapped in optical tweezers, are arranged into a well-defined arbitrary geometry before being transferred into low-angular momentum Rydberg states using laser pulses. Once in a Rydberg level, the atoms interact with each other through the dipole-dipole coupling, which enables to simulate the dynamics of arbitrary Hamiltonians [1,2].

However, the relatively short lifetime (in the 100 µs range) of low-angular momentum Rydberg atoms currently limits either the number of atoms or the duration of the simulation in order to ensure that none of the atom decays during the experiment. Longer lifetimes can be obtained by switching to high-angular momentum Rydberg states, like the circular states [3], but observing the spin dynamics over a long timescale requires trapping the low-laser-intensity-seeking alkali Rydberg atoms using complex hollow beam geometries [4].

This is one of the reasons that motivated many groups to develop Rydberg experiments with alkaline-earth or alkaline-earth-like elements. Rydberg states of divalent atoms have an optically active ionic core that can be used to manipulate the atoms. If, for laser-accessible Rydberg states, the optical excitation of the ionic core leads to the fast auto-ionization of the atom, the auto-ionization rate exponentially decreases as the angular momentum of the Rydberg electron increases. This opens the way to use the ionic core electron transitions to image, trap or cool alkaline-earth circular states.

During the last few years, we have developed a new experiment to prepare and manipulate circular states of strontium. We have demonstrated that it possible to use the ionic core transition to slow down a beam of strontium circular atoms by using a counter-propagating 422nm laser beam. We have also shown that the residual electrostatic interaction between the ionic core and the Rydberg electrons opens the way to manipulate the state of the Rydberg electron using laser beams resonant with ionic core transitions, or to encode the state of a Rydberg atom with a given n onto one of the magnetic sublevels of the metastable state $4d_{3/2}$. This opens the way to state-selective fluorescence imaging of circular states [5].

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Quantum simulation with Rydberg states of Erbium

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Neutral-atom arrays in optical tweezers have been demonstrated to be a reliable platform for quantum simulation and computing. In this context, the high complexity of lanthanides (e.g., Erbium [1]) translates into excellent prospects for their employment on quantum operations due to magical conditions, narrow-linewidth transitions and trappable Rydberg states, besides providing an 8-dimensional hyperfine manifold for the ground-state of the fermionic isotope Er167 [2].

Here, we present the latest developments in our implementation of a Quantum Simulator based on Rydberg states of Erbium. We have started by setting up a survey where we successfully identified and characterized roughly 550 states [3], including a direct excitation to an *ng*-state enabled by the submerged, 4f-shell of Erbium. We will soon start exploring novel Rydberg excitation schemes addressing large-angular-momentum states and possibly the high-dimensional hyperfine manifold of the fermionic isotope. This will enable applications of our platform both for quantum simulation of quantum field theories and quantum information processing through a qudit implementation on the hyperfine manifold of the fermionic ground-state.

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Observation of Rydberg blockade due to the charge-dipole interaction between an atom and a polar molecule

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Ultracold dipolar systems, including atoms excited to Rydberg states and polar molecules, hold great potential for quantum simulation and computation. Rydberg atoms offer strong, long-range interactions, which enable the engineering of quantum entanglement and multi-qubit gates through the Rydberg blockade mechanism. Polar molecules also exhibit long-range interactions and possess multiple long-lived rotational states that can be coupled using microwave fields to achieve high-fidelity quantum operations. Optical tweezer arrays have enabled the trapping of both these systems, creating the possibility of a hybrid system that combines the advantages of both platforms. This hybrid system offers new capabilities, including non-destructive readout of the molecular state [1], cooling of molecules using Rydberg atoms [2], and photoassociation of giant polyatomic Rydberg molecules [3].

In this talk, I will describe the first observation of Rydberg blockade due to the charge-dipole interaction between an atom and a polar molecule. Our experiment involves the creation of a hybrid system consisting of ultracold RbCs molecules and Rb atoms trapped in species-specific optical tweezers. We form weakly bound RbCs molecules by merging together optical tweezers containing Rb and Cs atoms and transfer the weakly bound RbCs molecules to the rovibrational ground state using stimulated Raman adiabatic passage. Finally, we observe blockade of the transition to the Rb(52s) Rydberg state due to the charge-dipole interaction with a RbCs molecule in the rovibrational ground state. The blockade we have observed provides a mechanism for conditional and non-destructive state readout of the molecule and opens up new research directions which I will briefly discuss.

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Speeding up trapped ion quantum processors via Rydberg interaction

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Trapped Rydberg ions are a novel approach for quantum information processing [1,2]. This idea joins the advanced quantum computing toolbox of trapped ions with strong dipolar interaction between Rydberg atoms. For trapped ions, this method can speed up entangling interactions and enables such fast operations in larger ion crystals.

In this presentation, I will first introduce the novel experimental platform of trapped Rydberg ions [2]. I will describe the specific physics involved when exciting ions into Rydberg states, the effects on the trapping potential due to the strong polarizability of Rydberg ions, and the controllable strong interaction between ion and motion. Moreover, I will summarize methods and results in speeding up trapped ion entanglement operations via the strong dipolar Rydberg interaction [3].

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Quantum Feature Maps for Graph Machine Learning on a Neutral Atom Quantum Processor

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Using a quantum processor to embed and process classical data enables the generation of correlations between variables that are inefficient to represent through classical computation. A fundamental question is whether these correlations could be harnessed to enhance learning performances on real datasets. We report the use of a neutral atom quantum processor comprising up to 32 qubits to implement machine learning tasks on graph-structured data. To that end, we introduce a quantum feature map to encode the information about graphs in the parameters of a tunable Hamiltonian acting on an array of qubits. Using this tool, we first show that interactions in the quantum system can be used to distinguish non-isomorphic graphs that are locally equivalent. We then realize a toxicity screening experiment, consisting of a binary classification protocol on a biochemistry dataset comprising 286 molecules of sizes ranging from 2 to 32 nodes, and obtain results which are comparable to those using the best classical kernels. Using techniques to compare the geometry of the feature spaces associated with kernel methods, we then show evidence that the quantum feature map perceives data in an original way, which is hard to replicate using classical kernels.

Spin squeezing by Rydberg dressing in an array of atomic ensembles

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Ensembles of neutral atoms enable state-of-the-art measurements of time, acceleration, and electromagnetic fields. Introducing entanglement in the form of spin squeezing among the constituent atoms offers a route to enhancing the precision of these measurements. In this talk, I will report on the creation of an array of spin-squeezed ensembles of cesium atoms via Rydberg dressing, a technique that offers optical control over local interactions between neutral atoms [1]. We optimize the coherence of the interactions by a stroboscopic dressing sequence that suppresses super-Poissonian loss. We thereby prepare squeezed states of $N = 200$ atoms with a metrological squeezing parameter $\xi^2 = 0.77(9)$ quantifying the reduction in phase variance below the standard quantum limit. We realize metrological gain across three spatially separated ensembles in parallel, with the strength of squeezing controlled by the local intensity of the dressing light. Our method can be applied to enhance the precision of tests of fundamental physics based on arrays of atomic clocks and to enable quantum-enhanced imaging of electromagnetic fields.

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Waveguide QED with Rydberg superatoms

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The field of Waveguide QED investigates how light in a single mode propagates through a system of localized quantum emitters. This driven, open system might turns into an interesting quantum many-body system if the coupling between individual photons and individual emitters is sufficiently strong. In this case, the photons mediate an effective interaction between the distant emitters, and the cascaded interaction between photons and saturable emitters can be interpreted as an effective interaction between individual photons.

We experimentally realize effective two-level emitters coupled to a single quantized mode by exploiting the Rydberg blockade effect of atomic ensembles to realize so-called Rydberg superatoms formed of N~10.000 atoms confined to a single blockaded volume. Due to the collective nature of a single excitation in the ensemble, the superatom effectively represents a single emitter coupling strongly to single photons. The directional emission of the superatom into the initial probe mode realizes a waveguide-like system in free-space without any actual light-guiding elements [1].

This talk will discuss how we scale this system from one to few strongly coupled superatoms to study how the propagation of quantized light fields through a small emitter chain results in photon-photon correlations and entanglement between the emitters. We also show how the internal dynamics of the superatom is reflected in the transmitted field [2], and we discuss how controlled dephasing of the collective excitation into collective dark states can be used to subtract exact photon numbers from an incoming light pulse [3].

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Novel Two- and Multi-Qubit Entangling Gates on Rydberg Atoms

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Improving the fidelity of two-qubit quantum gates gates is one of the key challenges for the continued development of neutral atom quantum processors. Additionally, the native implementation of entangling gates in three or more atoms can be of great benefit in many quantum computations. Here, we discuss several new protocols for performing two- and multi-qubit gates on Rydberg atoms.

The first class of protocols employs the Rydberg blockade mechanism. We use quantum optimal control methods to construct a family of global laser pulses implementing a two-qubit CZ or a three-qubit C_2Z gate. We identify pulses which minimize the error three common, major imperfections: Rydberg scattering, intensity inhomogeneity and Doppler shifts [1, 2]. To quantify the tradeoff between these errors, we evaluate the gate fidelity for the example of erasure-biased metastable ^{171}Yb qubits [3,4], and find that the pulse minimizing Rydberg scattering performs best in many realistic situations. We then consider the logical performance of these gates in the context of an error correction code, where we observe that gates robust against laser amplitude error and Doppler shifts often perform best, because they maintain the native large bias towards erasure errors. Our results significantly reduce the laser stability and atomic temperature requirements to achieve fault-tolerant quantum computing with neutral atoms.

The second class of protocols assumes a setup of two or more qubits coupled to a common cavity mode. We develop new gate schemes which implement non-local multi-qubit gates only by driving the cavity with a shaped classical pump pulse, while no driving of the qubits is necessary. We estimate the gate fidelity for Rydberg atoms coupled via a microwave cavity in the presence of the relevant losses.

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Microscopically-controlled arrays of alkaline-earth atoms

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Optical tweezer trapping of neutral atom arrays has been a rapidly progressing platform for quantum information science, enabling control and detection of 100s of individual atomic qubits, as well as optically-switchable long-range interactions. While pioneering work focused on alkali species, there has been recent exploration of a new type of atom - alkaline-earth(-like) atoms - for optical tweezer trapping [1-3]. While their increased complexity leads to challenges, alkaline-earth atoms offer new scientific opportunities by virtue of their rich internal degrees of freedom. I will report on how features of these atoms can cooperate with tweezer-based single-particle control to impact areas ranging from quantum information processing, to quantum metrology, and quantum simulation.

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High-dimensional SO(4)-symmetric Rydberg manifolds for quantum simulation

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We develop a toolbox for manipulating arrays of Rydberg atoms prepared in high-dimensional hydrogen-like manifolds in the regime of linear Stark and Zeeman effect. We exploit the SO(4) symmetry to characterize the action of static electric and magnetic fields as well as microwave and optical fields on the well-structured manifolds of states with principal quantum number n. This enables us to construct generalized large-spin Heisenberg models for which we develop state-preparation and readout schemes. Due to the available large internal Hilbert space, these models provide a natural framework for the quantum simulation of quantum field theories, which we illustrate for the case of the sine-Gordon and massive Schwinger models. Moreover, these high-dimensional manifolds also offer the opportunity to perform quantum information processing operations for qudit-based quantum computing, which we exemplify with an entangling gate and a state-transfer protocol for the states in the neighborhood of the circular Rydberg level.

Quench dynamics as a shortcut to adiabaticity in Rydberg atoms arrays

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The ability to prepare ground states of quantum Hamiltonians via an adiabatic protocol is typically determined by the smallest energy gap during quantum evolution. This poses a challenge for large quantum systems, in particular for instances where the minimum gap scales super-exponentially with system size. We experimentally investigate breakdown of the quantum adiabatic algorithms for such hard instances of the maximum independent set problem and demonstrate a method to circumvent this limitation. Using QuEra's Aquila programmable quantum simulator based on Rydberg atom arrays, we experimentally realize a hybrid adiabatic-quench-adiabatic protocol as a remedy to the diverging adiabatic timescale and find that it significantly outperforms adiabatic algorithms. We observe quantum-scar-like dynamics for different quench durations, demonstrating that a sweep-quench-sweep approach quantum algorithm can provide a shortcut to adiabaticity for a certain class of problems where adiabatic algorithms fail.

The many Faces of Ultracold Rydberg Interaction

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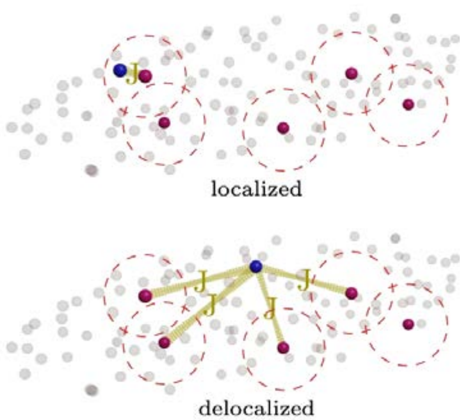
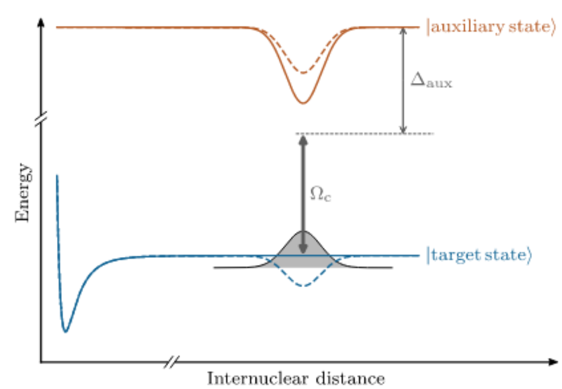
RPTU Kaiserslautern-Landau

Rydberg atoms show many different types of interaction depending on the interaction partner: From first-order C3 interaction between dipole-coupled different Rydberg states over second-order Van-der-Waals interaction between alike Rydberg states up to Fermi contact interaction between Rydberg and ground state atoms. While these interactions are known for quite some time now, it is still an active field of research to investigate the consequences arising out of them. From the plethora of few- and many-body effects found so far we already see first applications appearing in science and technology.

Here, I will cover the three aforementioned types of Rydberg interaction and will, on the one hand, detail on how the C3 interaction between Rydberg S- and P-states can be used to implement a random hopping spin model into an ultracold quantum gas and how indications for a localization cross-over appear in the system. On the other hand, focussing more on the Fermi contact interaction with ground state atoms, I will present how the Rydberg molecular potential can be used to tailor pair-potentials of low-lying atomic states up to a point where long range molecules of low lying states are created. Finally, I will show how the off-resonant C6 interaction between alike Rydberg atoms leads to facilitation dynamics resembling epidemic models with an absorbing-state phase transition or heterogeneous dynamics.



Localized and delocalized scenario in a C3-interacting random gas



Principle of engineering low-lying potentials by coupling it to an auxiliary Rydberg molecular potential

A molecular bond between ions and Rydberg atoms

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Atoms with a highly excited electron, called Rydberg atoms, can form unusual types of molecular bonds. The bond differs from the well-known ionic and covalent bonds not only by its binding mechanism, but also by its bond length ranging up to several micrometers. We report the observation a new type of molecular bond based on the interaction between the ionic charge and a flipping induced dipole of a Rydberg atom with a bond length of several micrometers. We measure the vibrational spectrum and spatially resolve the bond length and the angular alignment of the molecule using a high-resolution ion microscope. As a consequence of the large bond length, the molecular dynamics is slow and can be directly observed under the microscope. These results pave the way for future studies of spatio-temporal effects in molecular dynamics, e.g., beyond Born- Oppenheimer physics, and more generally on (ionic) impurities in quantum gases.

Universal Quantum Computation with Globally Driven Rydberg Atom Arrays

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University of Innsbruck, Austria

In this talk I present a model for quantum computation with Rydberg atom arrays, which only relies on global driving and Rydberg blockade and thus eliminated the requirement of local addressing of individual atoms. The scheme is based on dual-species arrays wit static trap positions. We present two ways to encode a quantum circuit: On option is to imprinted it in the trap positions of the atoms, and execute it by a sequence of global laser pulses; a second alternative is to use a universal arrangement of O(N^2) atoms to execute an arbitrary quantum circuit on N qubits, where the latter is solely encoded in the driving pulse sequence.

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Collective Light-Matter Interactions in Ultracold Rydberg Ensembles

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The exceeding high polarisability and strong mutual interaction of atomic Rydberg states has been an important resource for many applications that are currently pursued around the world. In this talk, I will discuss the collective light-matter coupling between propagating photons and Rydberg states in disordered atomic ensembles or regular arrangements of ultracold atoms. A particular focus will be placed on employing the strong Rydberg-Rydberg atom interaction to achieve large optical nonlinearities for the generation and manipulation of nonclassical states of light.

Scalable Qubit Arrays for Quantum Computation and Optimisation

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Quantum computation offers a revolutionary approach to how information is processed, offering new applications in material design, quantum chemistry and speed up of real-world optimisation problems, however a large number of qubits are required to obtain quantum advantage over classical hardware. Neutral atoms are an excellent candidate for practical quantum computing, enabling large numbers of identical qubits to be cooled and trapped, overcoming major barriers to scaling experienced by competing architectures. A crucial ingredient for quantum computing is the ability to perform controlled two-qubit gate operations, for which the strong, long-range dipole-dipole interaction between Rydberg atoms can be exploited to implement deterministic gate operations between atoms within a radius of $R < 10$ μm.

We present progress towards a new experimental platform for quantum computation at the University of Strathclyde, supported by the EPSRC Prosperity Partnership SQuAre with M Squared Lasers Ltd., based on reconfigurable atom arrays of up to 225 Cs atoms. We demonstrate high fidelity single qubit gate operations with errors below the threshold for fault tolerance using a non-destructive readout technique [1], along with work towards simultaneous trapping of arrays of ground and Rydberg states as the first step to creating a scalable architecture for quantum computing. These results pave the way towards performing high-fidelity two qubit and multi-qubit gate operations using a novel adiabatic rapid passage protocol [2] developed at Strathclyde, as well as exploring applications of the neutral atom system to solving classical optimisation problems.

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Circuit Model Quantum Computing with Neutral Atom Arrays

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Neutral atom arrays have demonstrated remarkable progress in the last few years to the point where they are a competitive platform for scalable circuit model quantum computing. Progress on improving gate fidelities, design of multi-qubit gate operations, low-crosstalk mid-circuit measurements, and the introduction of neural network based signal analysis for improved performance will be presented.

Scalable Architecture of Assembled Single-Atom Qubit Arrays in Two and Three Dimensions

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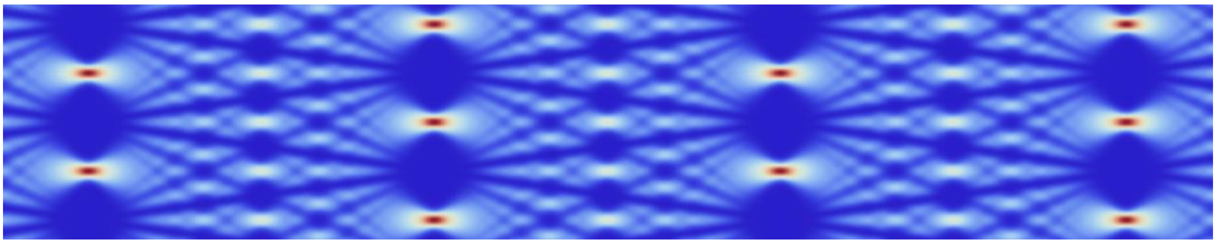

We report on the advancement of a novel platform for the creation of large-scale 3D multilayer configurations of planar arrays of individual neutral-atom qubits: a microlens-generated Talbot tweezer lattice which extends 2D tweezer arrays to the third dimension at no additional costs. We demonstrate the trapping, imaging, and sorting of rubidium atoms in Talbot planes [1].

In-plane atom transport enables the deterministic preparation of pre-defined 2D structures of more than 100 atoms [2] with exactly known mutual separations and selectable interaction strength. By adapting the geometry and the addressed Rydberg state, a parameter regime spanning from weak interactions to strong coupling can be accessed [3].

The Talbot self-imaging effect for microlens arrays constitutes a structurally robust and wavelength-universal method for the realization of 3D atom arrays with beneficial scaling properties. With more than 750 qubit sites per 2D layer, these scaling properties imply that 10 000 qubit sites are already accessible in 3D in our current implementation. The trap topology and functionality are configurable in the micrometer regime which we use to generate interleaved lattices with dynamic position control.

Directed towards a continuously operated neutral-atom quantum processor, we introduce a modular scheme built on an additional cold-atom reservoir and an array of buffer traps effectively decoupling cold-atom accumulation and single-atom supply from the quantum-register operation [4]. The results facilitate increased data rates and unlock a path to continuous operation of individual-atom tweezer arrays making use of discrete functional modules, operated in parallel and spatially separated.

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Towards new frontiers of quantum science with dual-species atom arrays

Giulia Semeghini

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In this talk, we will explore recent advancements in quantum science using Rydberg atom arrays and present future applications enabled by the use of a dual-species array based on a mixture of alkali and alkaline-earth atoms. Trapped arrays of interacting Rydberg atoms have become a leading platform for quantum information processing and quantum simulation due to their large system size and programmability. The use of two atomic species introduces the ability to store quantum information in one species and perform operations with the other, together with the possibility of selectively controlling inter and intra-species interactions for more flexible Hamiltonian engineering. These new features enable new and more efficient protocols for quantum error correction and collective quantum gates, and would allow access to a broader class of highly-entangled phases of matter. We will present our plans for a new experimental platform based on Yb and Rb atom arrays, which will take advantage of the different features of these two atomic species to create a flexible platform for quantum simulation and quantum information processing.

Designing tunable spin interactions in Rydberg tweezer arrays

Lea-Marina Steinert[1], Philip Osterholz[1], Ludwig Mueller[1], Roxana Wedowski[1], Arno Trautmann[1] and Christian Gross[1]

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Analog 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 XYZ-type spin-1/2 model, where the strong, short-range 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.

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Quantum computing with Yb Rydberg atoms

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Neutral atom quantum computing is a rapidly developing field. Exploring new atomic species, such as alkaline earth atoms, provides additional opportunities for cooling and trapping, measurement, qubit manipulation, high-fidelity gates and quantum error correction. In this talk, I will present recent results from our group on implementing high-fidelity gates on nuclear spins encoded in metastable 171Yb atoms [1], including mid-circuit detection of gate errors that give rise to leakage out of the qubit space, using erasure conversion [2]. I will also discuss ongoing spectroscopy of Yb Rydberg states, motivated by a new experiment to use circular Rydberg states to achieve even longer Rydberg lifetimes [3].

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QRydDemo - Quantum Computing with Rydberg Atoms

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The QRydDemo Consortium aims to realize a quantum computer demonstrator with up to 500 atomic qubits trapped in arrays of optical tweezers. Exciting the atoms with lasers to Rydberg states allows for rapidly switching interactions between the atoms on and off, enabling the implementation of fast and high-fidelity gate operations. Our quantum processor based on the optical tweezer architecture promises many exciting new possibilities. One novel aspect we aim to explore is the potential to change the qubit connectivity during a quantum computation. I will provide an overview of the QRydDemo project, theory insights into gate protocols, and demonstrate our online emulator that allows future users of our hardware to get familiar with QRydDemo's native gate operations.

Controlling a subwavelength atomic mirror using a single Rydberg atom

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Understanding and tuning light-matter interactions is essential for numerous applications in quantum science. Recently, a new avenue of light-matter interaction has been realized by exploiting the rich interplay of individual photons with structured subwavelength arrays of quantum emitters stored in a two-dimensional (2d) square optical lattice. These monolayers feature intriguing optical properties, including large cross-sections, a cooperative subradient response as well as directionality of the emitted light, turning the array into an efficient mirror [1].

In this talk, we present our recent findings, where we control the optical response of such an atomic mirror using a single ancilla atom excited to a Rydberg state [2]. We deterministically prepare the ancilla at the center of the array using the single-site resolution of our quantum gas microscope. Driving Rabi oscillations on the ancilla atom, we demonstrate coherent control over the transmission and reflection. Finally, increasing the mirror size directly reveals the spatial area around the ancilla atom where the switching is effective. Our results pave the way towards novel quantum metasurfaces and the creation of controlled atom-photon entanglement.

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Atomic ensembles meet qubits

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Quantum science promises great potential to revolutionize our current technologies. The past few years have witnessed a rapid progress on using arrays of individually trapped atoms as a programmable quantum processor. However, several challenges remain, including reconfigurable individual addressability for quantum operation and rapid non-demolish detection, which lead to limited efficiency in implementing quantum algorithm, low experimental repetition rate, and preclude applications of many quantum error correction protocols.

To address some of these difficulties, at MIT, we take an alternative approach based on arrays of atomic ensembles. By harnessing the collective optical response of the atomic ensemble, we demonstrate a rapid preparation, manipulation, and non-demolish readout of a single Rydberg qubit embedded in an atomic ensemble [1]. Scaling up the system towards large arrays of atomic ensembles has been achieved with apparatus upgrade, and preliminary results have demonstrated fast, parallel qubit readout. At the end of this talk, I will outline my proposed research at ETH, which aims for building a novel architecture for quantum computation/simulation with dual type dual-element atom arrays. I expect this architecture can further mitigate these challenges, including individual addressability and non-demolish selective detection.

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Abstracts of Posters

(in alphabetical order)

Non-adiabatic decay rates of charged Rydberg molecules

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Rydberg molecules, ranging from the so-called “trilobite” molecules to Rydberg macrodimers to Rydberg atom-ion molecules, are a stunning highlight of recent experimental progress in ultracold atomic physics. Typically, the lifetimes of these molecules are shorter than those of bare Rydberg atoms, suggesting that additional decay processes beyond radiative decay play an important role in their dynamics. In particular, non-radiative decay through non-adiabatic coupling between electronic potential energy curves could have a large effect. Non-adiabatic coupling can cause transitions between different electronic states and lead to the decay of the molecule. We investigate this mechanism here in the Rydberg atom-ion molecule system using the streamlined version of the R-matrix method to compute the positions and widths of the resonance states. We explore these resonances over a range of different principal quantum numbers. This study could be significant to other types of Rydberg molecules as well, as the potential curves which support the vibrational bound states are frequently coupled to dissociative potential curves.

Individual strontium atoms in a hybrid lattice-tweezer quantum simulator

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Neutral atoms in optical tweezer arrays are a powerful platform for analog quantum simulations. Configurable tweezer geometries are generated using liquid-crystal spatial light modulators and interactions between atoms can be controlled via coupling to Rydberg states. The initialization of neutral atom quantum simulators requires the preparation of single atoms cooled to the motional ground-state of the trap.

Here we report on the preparation of >150 strontium atoms in optical tweezer arrays at a wavelength of 520nm. We prepare single strontium atoms by loading optical tweezer arrays from a magneto-optical trap with a probability of 50% using light-assisted collisions in the tweezers. We implement resolved sideband cooling in the tweezers on the narrow intercombination line and quantify the cooling performance using sideband spectroscopy.

In addition, we characterize the fluorescence imaging in the tweezers using both repulsive Sisyphus cooling and sideband cooling and find the imaging survival probability to be limited to about 95% at our tweezer wavelength. Additionally, we characterize the imaging of individual atoms in an optical lattice at a wavelength of 1040nm and obtain low-loss and high fidelity imaging performance.

Combining optical tweezer arrays with lattices opens new perspectives to scale tweezer-based quantum simulators to larger system sizes and to an alternative preparation route of Hubbard systems in optical lattices without the need for evaporation.

Phase transitions in self-organized Rydberg facilitation dynamics

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In an off-resonantly driven cloud of atoms, the energy shift between two Rydberg states compensates the laser detuning for a specific interatomic distance. High enough driving strengths cause a spread of correlated excitations, the so-called facilitation. For low driving strengths, the dynamics are dominated by decay of Rydberg atoms and the spread of excitations is suppressed.

In between these active and absorbing phases, a non-equilibrium steady state phase transition is thought to occur. This phase transition is characterized by excitation avalanches. Disorder can introduce more complex phases where avalanches appear for large parameter ranges [1].

We experimentally investigate these phases in a cloud of thermal atoms driven by an off-resonant laser. Over time, the atomic density drops due to the loss of excited atoms by ionization. This process intrinsically pushes the system towards the phase transition from the active to the absorbing state [2]. Our results reveal a persistent algebraic distribution of excitation cluster sizes independent of starting parameters. We observe varying exponents which hint towards the influence of disorder in our system [3].

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Engineering lattice gauge theories with a Rydberg atom processor

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In the last years, Rydberg atoms in reconfigurable optical tweezers proved to be an excellent platform to implement Spin Hamiltonians in ultracold atom experiments [1]. An important subject in this matter is the exploration of Ising models with S = 1/2 and higher in one, two and three dimensions, including the investigation of gauge theories emerging in condensed matter physics [2]. As an example, I consider the well-known Rokhsar-Kivelson Hamiltonian, a 2D U(1) lattice gauge theory describing quantum dimer and spin-ice dynamics, in different geometries and investigate the resulting phase diagrams [3]. I explain how to engineer tunable anisotropic attractive as well as repulsive interactions with so-called superatoms by organizing two or more individual atoms in small clusters sharing one Rydberg excitation. The control of the couplings translates in blockade and antiblockade conditions arising in the dual formulation of the Rokhsar-Kivelson Hamiltonian [4]. In collaboration with experimentalists, I develop protocols to investigate this and other gauge theories with Rydberg atoms in reconfigurable tweezer arrays.

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Microlens-based tweezer arrays for Rydberg-interacting atoms

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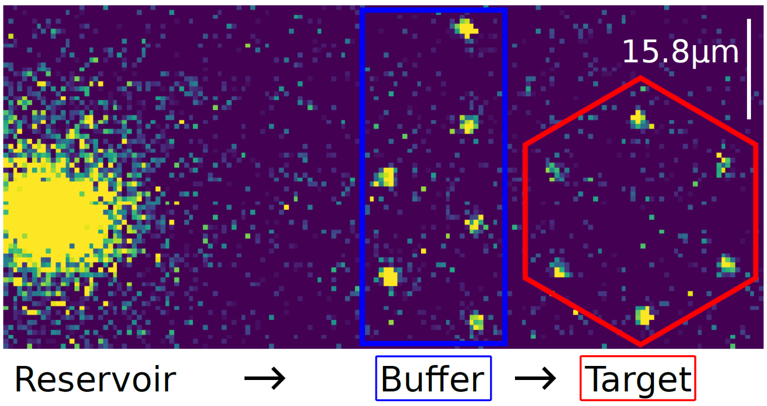
We report on a versatile platform of optical tweezers comprising hundreds of focused-beam dipole potentials capable to store laser-cooled atoms with spatial separations in the micrometer regime. Based on micro-fabricated lens arrays, this approach is highly scalable while offering three-dimensional tweezer configurations at no additional cost due to the inherent self-imaging. With more than 750 qubit sites per 2D layer, these scaling properties imply that 10 000 qubit sites are already accessible in 3D in our current implementation [1].
On this basis, defect-free 2D clusters of more than 100 single-atom quantum systems can be created [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. Rydberg-mediated interactions in assembled atom configurations are demonstrated [3].
A novel method for the deterministic preparation of individual atoms from a spatially separated cold-atom reservoir is introduced. The modular scheme effectively decouples cold-atom accumulation and single-atom supply from the quantum-register operation [4]. The results facilitate increased data rates and unlock a path to continuous operation of individual-atom tweezer arrays making use of discrete functional modules, operated in parallel and spatially separated.



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Converting microwave photons to infrared via room-temperature Rydberg atomic vapours

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Coherent upconversion from microwave to optical domain of light presents a formidable challenge due to the large difference between photon energies. Driven by the perspective of hybrid quantum networks, optically interconnecting superconducting microwave-based qubits remains one of the central tasks in this field, but other applications ranges from microwave astronomy to coherent imagers, to next-generation sensors. Many electro-optical and electro-optomechanical realisations have been presented [1] but most require specific conditions, such as cryogenic environments or laser-cooled trapped atoms. Here we undertake a simple approach to present a microwave-to-optical converter based on rubidium Rydberg vapours operating in a room-temperature [2], with the use of a simple setup [3]. We employ a 13.9 GHz transition between Rydberg energy levels as the input of the converter and observe coherently converted signal at an infrared 776 nm transition. Despite the simplicity, we achieve a wide conversion bandwidth of 16 MHz and a conversion dynamic range of 57 dB. These properties, together with very low intrinsic noise of conversion, allow us to observe free-space microwave thermal radiation coupling to the converter. We confirm this by applying single photon counting on the converted signal and performing temporal autocorrelation measurement. This way we observe Hanbury Brown and Twiss effect of thermal photon bunching, in agreement with parameter-free theory. Furthermore, we show that introducing coherent microwave radiation allow us to observe interference between coherent and thermal states of photons in the converted microwave radiation. These results highlight the performance of the proposed converter model and point to the versatile applications of conversion.

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Charged ultralong-range Rydberg trimers

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We show that the recently observed class of long-range ion-Rydberg molecules [1] can be divided into two families of states, which are characterised by their unique electronic structures resulting from the ion-induced admixture of quantum defect-split Rydberg nP states with different low-field seeking high-l states. We predict that in both cases these diatomic molecular states can bind additional ground state atoms lying within the orbit of the Rydberg electron, thereby forming charged ultralong-range Rydberg molecules (ULRM) with binding energies similar to that of conventional non-polar ULRM [2]. To demonstrate this, we consider a Rydberg atom interacting with a single ground state atom and an ion. The additional atom breaks the system's cylindrical symmetry, which leads to mixing between states that would otherwise be decoupled. The electronic structure is obtained using exact diagonalisation over a finite basis and the vibrational structure is determined using the Multi-Configuration Time-Dependent Hartree method. Due to the lobe-like structure of the electronic density, bound trimers with both linear and nonlinear geometrical configurations of the three nuclei are possible. The predicted trimer binding energies and excitation series are distinct enough from those of the ion-Rydberg dimer to be observed using current experimental techniques.

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Out-of-equilibrium physics in a disordered dipolar Heisenberg quantum spin system

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Generically, it is believed that a non-integrable interacting closed quantum system thermalizes. However, in recent years there has been a shift of paradigm that disorder can possibly lead to either the absence of thermalization as observed in many-body localized systems, or to the emergence of a prethermal state which prevents thermalization on experimentally accessible timescales. Inspired by these phenomena, we tested experimentally using a dipolar interacting Rydberg gas whether a Heisenberg spin system with disorder in the couplings between two spins thermalizes. As a result, we found that such a dipolar interacting Heisenberg XXZ system does not thermalize on experimental timescales in the presence of strong disorder, but instead reaches a prethermal regime. As a consequence of prethermalization, an effective description of the Hamiltonian as an ensemble of pairs become possible.[1] As a result, we observe universal spin relaxation independent of the anisotropy parameter of Heisenberg XXZ Hamiltonians.[2]
Another phenomenon found in spin systems with random couplings is the spin glass phase, which was very early found in classical systems, but was only recently realized in the quantum regime for very special coupling distributions. The spin glass phase is usually associated with slow relaxation dynamics and aging. Aging describes the effect that after the system reaches a quasi-equilibrium, the linear response of the system depends on the time it spends in the quasi-equilibrium regime. We will present indications of aging, which serves as a first signature that a disordered Heisenberg spin system with dipolar couplings might also show a spin glass phase.

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A new machine with programmable arrays of Ryberg ytterbium atoms for quantum computing applications

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I will present a new experiment based on Rydberg ytterbium (Yb) atoms in programmable arrays of optical tweezers that will be realized in Florence as a joint effort of CNR-INO, the Physics Department pf the University of Florence and LENS. This machine, funded by the National Recovery and Resilience Plan, will be realized in the context of the newly established National Center for HPC, Big Data and Quantum computing. The setup is currently under design, and its construction will start by the end of summer 2023.
In this new machine, the two nuclear spin states of fermionic ^{171}Yb will be used as robust and long-lived qubit states, while excitation to Rydberg states will be exploited to realize multi-qubit operations. Once complete, this new experimental setup will be open to interactions with other research institutes as well as industrial partners and will allow for the investigation of quantum computing techniques for real worlds use-cases and applications.

Generation of two-dimensional bottle beam arrays of arbitrary geometries for atom trapping with a spatial light modulator

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We generate two-dimensional bottle beam arrays for laser trapping of atoms in the ground and Rydberg states. A dipole-trap laser beam is diffracted by a phase spatial light modulator imprinted with a phase hologram to generate two dimensional arrays of bottle beam of arbitrary geometries. We found that the phase hologram calculated by the Gerchberg-Saxton (GS) algorithm, typically used in cold atom community, may cause a certain fraction of defects in the generated bottle beams, depending on the phase range of the initial guess and the array geometry, as shown in Fig. 1. We have developed a modified optimal beam splitting (BS) algorithm to calculate the phase hologram and no defects are found in all calculated array geometries. We demonstrate the generation of bottle beam arrays of various geometries, which may open appealing applications in quantum information processing and simulation based on Rydberg atoms.

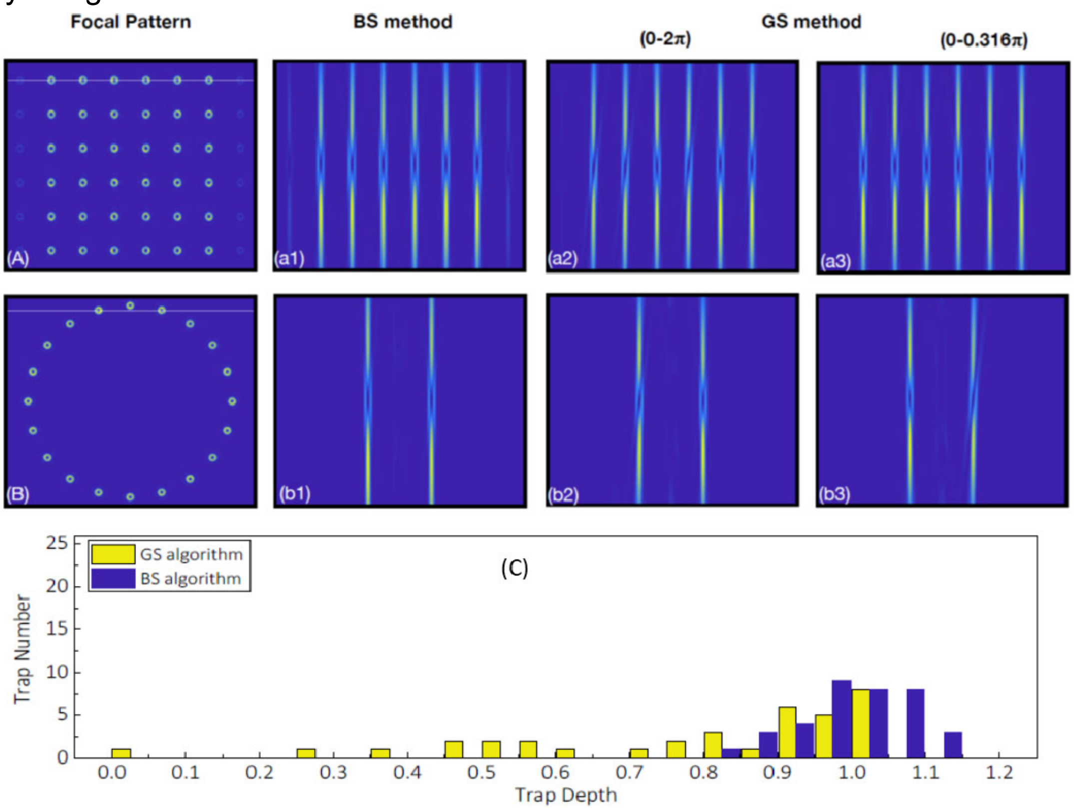

Figure 1. (A) 6-by-6 bottle beam arrays and (B) a ring of 20 bottle beams generated by the BS algorithm. (a1)-(a3) and (b1)-(b3) the intensity distribution along the beam propagating direction for the bottle beams along the line in (A) and (B), respectively. (a1) and (b1) are generated by the BS algorithm. (a2), (b2) and (a3), (b3) are generated by the GS algorithm but the phase range for the random initial guess are (0-2π) and (0-0.316π), respectively. (C) a distribution of trap depth for the 36 bottle beams of (A) generated by BS (blue) and GS (yellow) alrogithm.

High-dimensional SO(4)-symmetric Rydberg manifolds for quantum simulation

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We develop a toolbox for manipulating arrays of Rydberg atoms prepared in high-dimensional hydrogen-like manifolds in the regime of linear Stark and Zeeman effect. We exploit the SO(4) symmetry to characterize the action of static electric and magnetic fields as well as microwave and optical fields on the well-structured manifolds of states with principal quantum number *n*. This enables us to construct generalized *large-spin* Heisenberg models for which we develop state-preparation and readout schemes. Due to the available large internal Hilbert space, these models provide a natural framework for the quantum simulation of quantum field theories, which we illustrate for the case of the sine-Gordon and massive Schwinger models. Moreover, these high-dimensional manifolds also offer the opportunity to perform quantum information processing operations for qudit-based quantum computing, which we exemplify with an entangling gate and a state-transfer protocol for the states in the neighborhood of the circular Rydberg level.

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Probing dense Rydberg gases excited by ultrashort laser pulses

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Ultrashort laser pulses provide pathways for manipulating atomic quantum gases on femtosecond timescales. By focusing a single laser pulse with 166 fs duration onto a cloud of ultracold Rb-87 atoms, the formation of complex many-body systems with long-range interaction can be triggered.

Below the two-photon ionization threshold, we observe the formation of a dense Rydberg gas due to the large bandwidth of the femtosecond laser pulse, which bypasses the Rydberg blockade effect. By tuning the wavelength of the short pulse, we can address different Rydberg states as well as a mixture of neighbouring states closer to the ionization threshold, resulting in different subsequent dynamics.

Our setup allows direct measurement of the maximum kinetic energy of photoelectrons and ions. After ionizing the Rydberg states with an infrared laser pulse, the kinetic energy of the photoelectrons allows distinguishing between low lying states with a principal quantum number between $n = 10$ and 12 and higher lying states. The kinetic energy of the ions reflects the amount of Coulomb energy in the system, which depends on the amount of ionized Rydberg states as well as the density of the target. Comparison with molecular dynamics simulations provides deep insights into the underlying dynamics driven by long-range Coulomb interactions.

To further enhance our detection method, a coincidence detection unit consisting of a high-resolution ion microscope and a Velocity-Map-Imaging spectrometer is under construction. The new detection unit will allow a pulsed extraction and the subsequent simultaneous measurement of the spatial distribution of ions with a simulated spatial resolution of 100 nm and the momentum distribution of electrons with a relative resolution of 10% over six orders of magnitude. This enables the investigation of atom ion hybrid systems and the dynamics of bound states with long-range interaction.

Programmable quantum simulator with Strontium Rydberg atoms in optical tweezer arrays

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Electronically highly excited (Rydberg) atoms constitute a system with controllable long range interactions which allows to study and simulate many intriguing phenomena, ranging from quantum non-linear optics to quantum magnetism and dipole-mediated energy transport [1]. The underlying dynamics depend on the structure, dimensionality and interaction type of the physical system. Disentangling and controlling their contributions is an open problem, whose solution may empower new technology, including realizing general purpose quantum computers.
Such challenge is addressable by studying model systems in highly controllable experiments that capture their key features. Ultra-cold interacting Rydberg Strontium atoms trapped in reconfigurable arrays of optical tweezers represent such tailored quantum simulator. Strontium provides several sets of atomic states, including metastable ones [2], that are conveniently mappable into magnetic spins or quantum bits. Single- or two-photon excitation pathways to nS, nP and nD Rydberg states allow to engineer and fine-tune dipole-mediated interactions that can picture different spin or energy transport scenarios and also realize quantum gates [3]. I will present our progress with the construction of the setup and outline our planned capabilities, including the creation of up to three-dimensional large structures of optical tweezers with single site addressability and manipulation ability.

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EIT-based detection of Rydberg atoms for quantum simulation with cesium atomic ensembles

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A novel method of preparation and detection of Rydberg atoms in atomic ensembles was recently demonstrated on rubidium by Xu *et al.* [1]. We present the plan to implement the same principles on cesium. The method will be implemented on an array of atomic ensembles prepared by using time-multiplexed optical tweezers [2]. With out previous setup we were able to demonstrate the preparation of arrays of up to 74 atomic ensembles consisting of ∼100 atoms on average.

The detection is based on electromagnetically induced transparency on ladder scheme, where the upper level is the Rydberg state. Its energy is shifted when a Rydberg atom is present in the atomic ensemble, causing the transmission of the signal beam to decrease compared to when all atoms are in the ground state. Since the method relies on a phenomenon that does not involve absorption of photons, it is expected to be non-destructive, which was experimentally confirmed in the abovementioned article [1].

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Experimental validation of the Kibble-Zurek mechanism on a digital quantum computer

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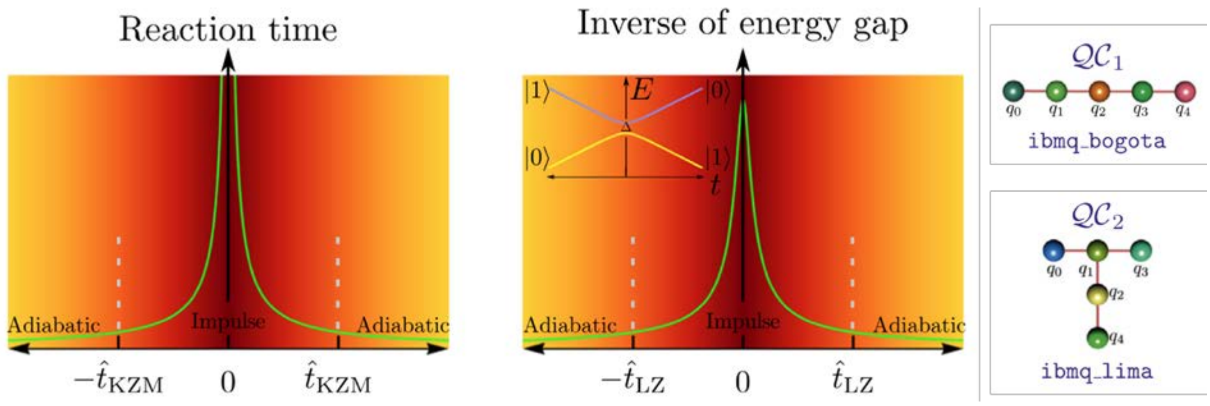
The Kibble-Zurek mechanism (KZM) captures the essential physics of nonequilibrium quantum phase transitions with symmetry breaking. KZM predicts a universal scaling power law for the defect density which is fully determined by the system's critical exponents at equilibrium and the quenching rate. We experimentally tested the KZM for the simplest quantum case, a single qubit under the Landau-Zener evolution, on an open access IBM quantum computer (IBM-Q). We find that for this simple one-qubit model, experimental data validates the central KZM assumption of the adiabatic-impulse approximation for a well isolated qubit. Furthermore, we report on extensive IBM-Q experiments on individual qubits embedded in different circuit environments and topologies, separately elucidating the role of crosstalk between qubits and the increasing decoherence effects associated with the quantum circuit depth on the KZM predictions. Our results strongly suggest that increasing circuit depth acts as a decoherence source, producing a rapid deviation of experimental data from theoretical unitary predictions.



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Realistic scheme for quantum simulation of Z2 lattice gauge theories with dynamical matter in (2+1)D

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Gauge fields coupled to dynamical matter are ubiquitous in many disciplines of physics, ranging from particle to condensed matter physics, but their implementation in large-scale quantum simulators remains challenging. Here we propose a realistic scheme for Rydberg atom array experiments in which a Z2 gauge structure with dynamical charges emerges on experimentally relevant timescales from only local two-body interactions and one-body terms in two spatial dimensions. The scheme enables the experimental study of a variety of models, including (2 + 1)D Z2 lattice gauge theories coupled to different types of dynamical matter and quantum dimer models on the honeycomb lattice, for which we derive effective Hamiltonians. We discuss ground-state phase diagrams of the experimentally most relevant effective Z2 lattice gauge theories with dynamical matter featuring various confined and deconfined, quantum spin liquid phases. Further, we present selected probes with immediate experimental relevance, including signatures of disorder-free localization and a thermal deconfinement transition of two charges.

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THz Polarization Spectroscopy of Rubidium Rydberg atoms

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We report on polarization sensitive detection of radiation from a solid-state THz emitter using a centimeter-sized rubidium vapour cell. Similar work has previously been carried out in the microwave domain[a]. The atoms are probed in an electromagnetically induced transparency (EIT) ladder-scheme, where two laser fields connect ground-state atoms to a Rydberg state. Incoming THz radiation creates coupling between Rydberg states which modifies the EIT signal and depending on the particular Rydberg states in play, we observe dramatically different signatures of the THZ field polarization being scanned. We interpret our observations qualitatively using a dressed state picture and model our data quantitatively using full density matrix calculations.

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Quantum feature maps for graph machine learning on a neutral atom quantum processor

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The manipulation of neutral atoms by light is at the heart of countless scientific discoveries in the field of quantum physics in the last three decades [1]. The level of control that has been achieved at the single particle level within arrays of optical traps, while preserving the fundamental properties of quantum matter (coherence, entanglement, superposition), makes these technologies prime candidates to implement disruptive computation paradigms. For instance, using such a quantum processor to embed and process classical data enables the generation of correlations between variables that are inefficient to represent through classical computation [2]. A fundamental question is whether these correlations could be harnessed to enhance machine learning performances on real life datasets.

To that end, we introduce a quantum feature map to encode the information about graphs in the parameters of a tunable Hamiltonian acting on an array of qubits. Using this tool, we first show that interactions in the quantum system can be used to distinguish non-isomorphic graphs that are locally equivalent. We then realize a toxicity screening experiment, consisting of a binary classification protocol on a biochemistry dataset comprising 286 molecules of sizes ranging from 2 to 32 nodes, and obtain results which are comparable to those using the best classical kernels. Using techniques to compare the geometry of the feature spaces associated with kernel methods, we then show evidence that the quantum feature map perceives data in an original way, which is hard to replicate using classical kernels.

See here for the full article.

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Sub-nanosecond laser excitation of ultracold atoms: towards ultrafast quantum computers and super-radiance studies

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We have investigated ultrafast many-body dynamics of Rydberg atoms successfully with picosecond pulsed lasers [1, 2]. However, for encoding quantum information in the hyperfine levels of the ground state, as is demonstrated in neutral atom quantum computers [3, 4], the spectral width needs to be narrower than several GHz for those hyperfine levels to be resolved. In this study, we developed a new sub-nanosecond laser system with controllable pulse duration, which compromises the resolution of hyperfine levels and the ultrafast excitation.

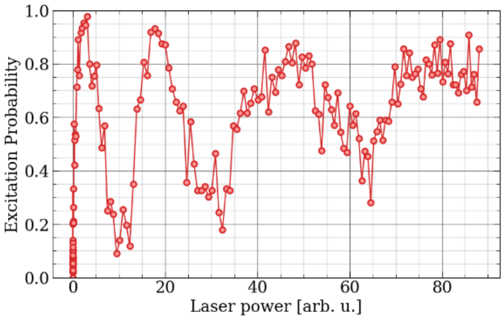

Figure 1. Excitation probability with an ~800 ps pulse as a function of the laser power.

We constructed a fiber-based Mach-Zehnder interferometer with an electro-optical phase modulator to slice 780 nm continuous-wave laser light into sub-nanosecond pulses. The pulse duration can be controlled from 50 ps at shortest. The extinction ratio is enhanced to be ~50 dB by a commercial electro-optical intensity modulator, and further enhanced by an acousto-optical modulator and a semiconductor optical amplifier on a 10 ns timescale. We performed coherent excitation of ^{87}Rb atoms trapped in optical tweezers from $5S_{1/2}$ *F*=2 state to $5P_{3/2}$ *F*'=3 state. By changing the laser power of ~800 ps pulses, as shown in Fig. 1, we observed the Rabi oscillation with the maximum contrast of more than 90%, which confirmed the sub-nanosecond coherent laser excitation. This laser system would be useful for ultrafast two-qubit gate operations of neutral atom quantum computers [1], as well as for the time-resolved study of the super-radiance from ordered atoms.

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Robust control and optimal Rydberg states for neutral atom two-qubit gates

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Abstract

Neutral atoms trapped in optical tweezers provide a scalable platform towards realizing a quantum computer. Strong, long-ranged interactions are obtained by exciting these atoms to electronic states with high principal quantum numbers *n,* termed *Rydberg states* **–** these can be leveraged to make multi-qubit gates, the building blocks of quantum computation. Various factors – such as spontaneous emission from the Rydberg state and laser intensity noise – can contribute to infidelity of such gates. With the aid of quantum optimal control (QOC) theory, we optimize the experimental control parameters to obtain high-fidelity, robust gates. With QOC, one can incorporate constraints naturally to devise gates that obtain the highest fidelities given specific experimental limitations.

Control system and architecture for a Rydberg quantum processor

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At the University of Strasbourg, we are upgrading our Rydberg atom digital quantum simulator with fully programmable, multi-scalable and agile control software [1] and hardware [2]. This provides the possibility to generate arbitrary waveforms on-the-fly to create instances for realizing robust quantum gates and quantum algorithms, including the possibility for mid-circuit measurements and feedback [3]. The simulator has also been upgraded with a new microwave system for driving different Rydberg states within 40GHz range, which enables us to investigate controllable dissipative quantum dynamics and entanglement generation in atomic arrays of micro-ensembles and single atoms.

Our building blocks are Rydberg qubits that could be encoded using a combination of excited states e.g., nS and nP for *rr-qubits* or two hyperfine ground states for *gg-qubits* of Potassium-39 with lifetimes T_1 of hundreds of microseconds and hundreds of milliseconds time-scale, respectively. Initial observations show *rr-qubit* coherence times of T_2^* ~6 us in our experimental setup.

I will also present our initial design for a new computational element which could serve as an architecture for Rydberg quantum registers based on *rr-* and *gg-qubits* encoding, that we call "*flip-flop quantum register*" within arrays of atoms, whose state will be protected against decoherence when implementing quantum computing protocols [4] [5].

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Characterizing Operator Growth in Disordered Quantum Spin Systems via Out-of-Time-Ordered Correlators

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We investigate operator growth and information propagation in disordered, isolated quantum spin systems using out-of-time-ordered correlators (OTOCs) as a diagnostic tool. Specifically, we characterize the evolution of OTOCs of two initially local Pauli operators in one-dimensional XXZ Heisenberg models using numerically exact techniques. We survey both ordered and the disordered systems with random on-site potentials that in the limit of strong disorder lead to many-body localization (MBL). While in ordered spin chains, operator growth is almost indistinguishable for power-law ($\alpha \geq 3$) and nearest-neighbour interactions, we observe a much faster growth in power-law interacting systems with strong on-site disorder than in their nearest-neighbour interacting counterparts. The light cones observed in the case of power-law interactions and strong disorder are found to be power-law, rather than logarithmic. Additionally, we propose an experimental method for measuring OTOCs with Rydberg-excited atoms through an echo scheme and analyze advantages and disadvantages of different classes of initial states to optimize measurement. Last but not least, I give an outlook on my PhD project on complex system dynamics in structured Rydberg gases.

Rydberg Simulator: From QCD to Random Ensemble States

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Rydberg setups are versatile platforms for simulation owing to their highly tunable strong interactions. I will discuss two separate scenarios where one dimensional configuration of trapped Rydberg atoms demonstrate its unique usefulness in the quantum simulation of novel physics. The first example emulates the physics of forming hadronic states during the inelastic collision of mesons using Rydberg-dressed atoms [1,2]. The second example deals with the efficient characterisation of quantum state designs that are realised on a Rydberg platform [3]. While the first example highlights the benefits of optically controlling the strength and shape of the effective potentials derived from Rydberg dressing, the latter is an example of exploiting machine learning techniques to characterise the randomness in an ensemble of states that are obtained from the chaotic many-body Rydberg dynamics.

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Quantum simulation with circular states of strontium

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Quantum simulation is one of the main developing quantum technologies. The goal is to simulate the dynamics of many-body system with another quantum system, in which we can control every parameter.

Many systems are being investigated to implement a quantum simulator (superconducting qubits, trapped ions, cold atoms in optical lattices…). Rydberg atoms trapped in optical tweezers, in particular, is a very versatile platform being developed in several groups. Up to hundreds of ground states atoms are trapped in optical tweezers and re-arrange in arrays with arbitrary geometry configuration. The ground state atoms are then transferred by laser excitation to low angular momentum Rydberg states. These highly excited states exhibit a very strong dipole-dipole coupling between neighboring atoms that can be tuned by adjusting the array orientation or by applying microwave dressing. This enables to simulate arbitrary spin Hamiltonians, or study their many-body dynamics. In our group we use Circular Rydberg states, which are states with maximum angular momentum [1]. When placed in a cryogenic environment that suppress black-body radiation, the lifetime of circular states can reach up to tens of milliseconds as opposed to low-angular momentum Rydberg states that have a lifetime in the 100 µs range.

Alkali circular states can be trapped with focused laser beams using the ponderomotive potential of the almost free Rydberg electron, making it possible to study the simulated spin dynamics over long time scale. In the case of alkaline-earth atoms however, the large polarizability of the ionic core allows to directly trap the circular state in optical tweezer. The optical transitions of the ionic core also provide a way to detect the Rydberg atoms. Furthermore, if the core electron is in an excited state with a non-zero electric quadrupole moment, its coupling to the Rydberg electron will induce an energy shift in the ionic core energy levels. This energy shift depends on the principal quantum number n of the circular state. It can be measured by Raman spectroscopy of the ionic core, opening the way to perform QND measurement of the circular state [2].

The goal of my PhD thesis is to develop a new experiment, in which we trap single atoms of circular state of strontium in optical tweezers and use the coupling between the two electrons to perform QND measurement of the circular state or quantum gates operations with the long-term goal of creating a quantum simulator.

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Rydberg quantum optics in ultracold Ytterbium gases

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Mapping the strong interaction between Rydberg excitations in ultracold atomic ensembles onto single photons paves the way to realize and control high optical nonlinearities at the level of single photons [1]. Demonstrations of photon-photon gates or multi-photon bound states based on this concept have so far primarily employed ultracold alkali atoms [2,3]. Two-valence electron species, such as Ytterbium, offer unique novel features namely narrow-linewidth laser-cooling, optical detection and ionization, and long-lived nuclear-spin memory states [4].

On this poster, we present our ultracold Ytterbium apparatus designed for few-photon Rydberg quantum optics experiments. The system is optimized for fast production of large, thermal ytterbium samples, to study the interactions between a large number of Rydberg polaritons simultaneously propagating through a medium with extremely high atomic density. Specifically, we discuss our two-chamber setup with 2D/3D two-color MOT configuration, and our progress towards Rydberg excitation of optically trapped Ytterbium atoms.

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Exact two-body bound states and dynamics of dopants in Ising antiferromagnets

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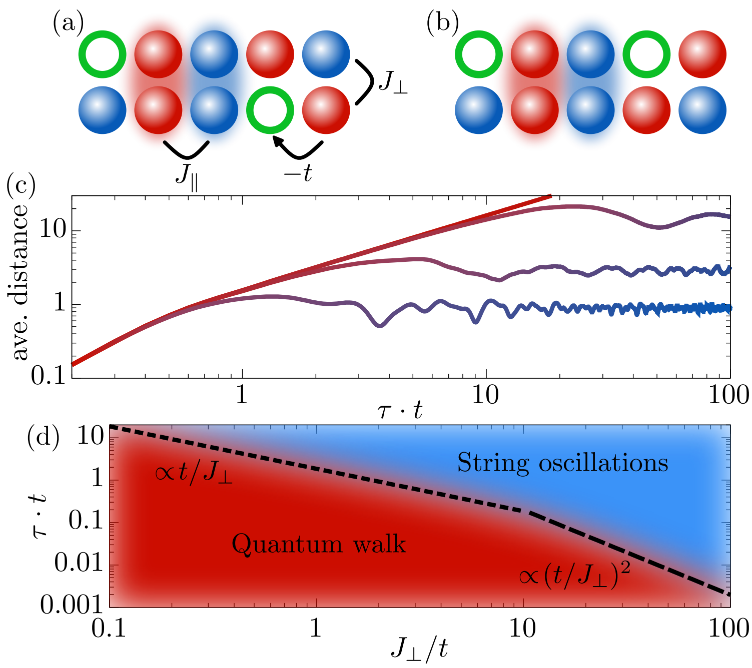
The motion of dopants in quantum spin environments is crucial to the understanding of strongly correlated systems. In particular, the potential binding of two dopants should lead to key insights into the microscopic origin of high-temperature superconductivity. Motivated by the new opportunities in quantum simulation experiments with ultracold atoms in optical lattices and Rydberg atoms in tweezer arrays, I study scenarios in which we may gain exact insights into the binding and dynamics of two such dopants [1,2,3]. In idealised Bethe lattices with Ising-type spin interactions, I show that the dopants always bind, and support a p- or d-wave symmetric wave function. I also unveil a Pauli blocking mechanism that makes the rotationally symmetric s-wave states unbind [2]. Furthermore, in two-leg ladders with motion only along one spatial (Figs. 1(a)-1(b)), I show that dopants may bind strongly to each other. Finally, I exactly characterise the non-equilibrium quench dynamics (Figs. 1(c)-1(d)), following the sudden creation of two dopants next to each other in such a lattice [3]. The latter scenario is particularly well-suited for inquiry in Rydberg tweezer arrays, in which the spin interactions may be tuned at will [4]. Such investigations should be able to demonstrate the non-equilibrium crossover dynamics from the initial quantum walk of the dopants, to the long-time oscillatory motion driven by the presence of undamped string excitations akin to recent results for 2D square lattices [5,6].



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Analogue Quantum Computing and Blue-Detuned Bottle Traps in Caesium Rydberg Atom Arrays

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The experimental platform developed at Strathclyde uses dynamically reconfigurable arrays of single ^{133}Cs atoms in holographically-generated optical dipole traps (ODTs) to perform analogue quantum simulations with highly excited Rydberg states. By choosing inter-atomic separations within the Rydberg blockade radius and applying amplitude- and frequency-shaped Rydberg excitation pulses, we can coherently evolve the system Hamiltonian through its ground states. Here we demonstrate our experimental results for a 1D Ising model spin chain simulation used as a benchmark for our platform's capabilities before moving on to more complex 2D geometries and maximum independent set (MIS) type problems. Our results show we can prepare Z_2 ordered many-body states made up of up to 11 atoms with target state probabilities exceeding 40% without correcting for imperfect state detection fidelities.

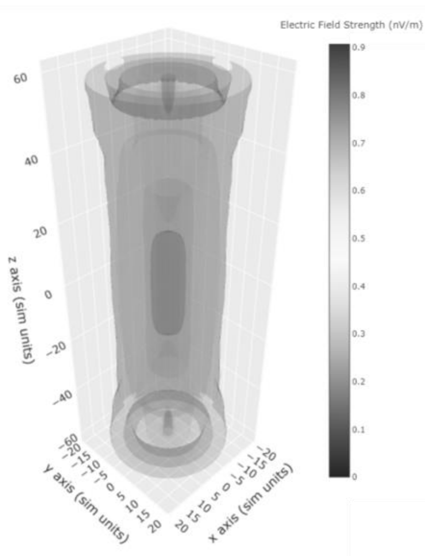

Figure 1. Simulated blue-detuned optical dipole trap potential for ^{133}Cs atoms

So far, most experiments of this kind have used red-detuned ODTs which must be switched off during Rydberg excitation because they are anti-trapping for these highly excited states. The undesirable effect of this approach is that it limits the maximum algorithm duration and the operation fidelity because the atoms are in free fall for the duration of the quantum simulation algorithm. We address this issue with novel, blue-detuned holographic bottle beam traps which can trap both Rydberg and ground state atoms in a light intensity minimum as shown in Figure 1. By dynamically transferring atoms between arrays of blue and red-detuned ODTs, we can access the best of both methods. Deep, red-detuned traps are used for loading atoms from a magneto optical trap and applied for Rydberg state detection, whilst the reduced AC Stark shift and Rydberg atom confinement properties of the blue-detuned traps are employed during the quantum simulation algorithm for improved performance. Here we present our initial results for trapping of ground and Rydberg atoms in arrays of blue-detuned ODTs, as well as successful atom transfer between red- and blue-detuned traps with a view of applying these techniques to quantum simulation algorithms in the near future.

Optimal control for Rydberg atom quantum computation

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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, such as long coherence times and entanglement via strong dipole-dipole interactions by driving them to highly excited Rydberg states. In this contribution, we show how the use of sophisticated optimal control techniques can boost the development of this technology to realize a Rydberg atom quantum processors with several hundred qubits in the upcoming years.

Precision spectroscopy and modeling of Yb Rydberg states for neutral atom quantum computing

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Alkaline-earth-like atoms such as ytterbium have a rich energy level structure, making them a versatile tool for quantum computing and simulation. A precise knowledge of their complex energy level structure is important for the accurate understanding of interaction strengths and decay dynamics.

In this contribution, I will present the results of precision laser and microwave spectroscopy of Yb Rydberg atoms using an atomic beam apparatus. The precision spectroscopic results serve as a test bed for the development of a comprehensive MQDT model for isotopes of Yb with zero (^{174}Yb) and nonzero (^{171}Yb) nuclear spin. The predictions of the MQDT model will be compared to measured interaction strengths and lifetimes of Rydberg atoms in an optical tweezers setup.

A new strontium quantum simulator using arrays of Rydberg atoms for simulating lattice gauge theories

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Ultracold neutral atoms have proven to be a suitable platform for the study of many-body physics. In particular, in the last decade excited atoms to Rydberg states together with the capability of individually addressing them in programmable optical tweezers have been used to engineer spin-Hamiltonians [1]. An example of such Hamiltonians is the Ising model which accounts for the magnetization of condensed matter systems. More recently, there have been proposals to implement with Rydberg atoms lattice gauge theories relevant in condensed matter physics as well as high energy physics.

This work comprises the early steps towards the construction of a new ultracold atom experiment using strontium Rydberg atoms trapped in a programmable tweezer array. Firstly, I motivate the interest in strontium Rydberg atoms. Then, I present an overview of the design of the experiment including the vacuum system, the laser cooling and trapping and the electromagnetic field control. Finally, I discuss on long-term perspectives of the apparatus, which is meant to provide a platform for the study of 2D emerging U(1) lattice gauge theories in decorated Rydberg atom arrays, using a so-called superatom approach [2].

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Quantum Computation with Neutral Alkaline-Earth-like Ytterbium Rydberg Atoms in Optical Tweezer Arrays

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Experiments with neutral cold atoms trapped in reconfigurable optical tweezer arrays have recently developed into one of today's leading platforms for quantum simulation and computation, due to the innate scalability, single atom control and a Rydberg-induced blockade mechanism for generating entanglement.

However, achieving fault-tolerant quantum computing with Rydberg atom arrays, still requires improvement of currently achievable fidelities in preparation, gate operation and read-out.

Recent tweezer experiments utilizing the alkaline-earth-like atom ytterbium-171 promise a multitude of advantages to overcome present limitations, such as its highly coherent metastable 'clock' state, a two valence-electron structure and single-photon Rydberg transitions.

Novel qubit architectures [1-3] exploit these unique properties to encode nuclear qubits in the ground and metastable states, suggesting moderate requirements for experimental parameters, while new error correction schemes [2, 4] specifically tailored towards this isotope convert detected leakage from the qubit subspace into traceable errors.

In this poster we present our pathway of building a Rydberg tweezer experiment utilizing the alkaline-earth-like atom ytterbium-171. Main milestones include the characterization of two microscope objectives, the construction of magnetic coils along with electric field compensation and the implementation of homogeneous 2D tweezer holograms along with mobile dipole traps.

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Magnetism in the two-dimensional dipolar XY-model

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Motivated by a recent experiment on a square-lattice Rydberg atom array realizing a long-range dipolar XY model [Chen et al., Nature (2023)], we numerically study the model's equilibrium properties. We obtain the phase diagram, critical properties, entropies, variance of the magnetization, and site-resolved correlation functions. We consider both ferromagnetic and antiferromagnetic interactions and apply quantum Monte Carlo and pseudo-Majorana functional renormalization group techniques, generalizing the latter to a U(1) symmetric setting. Our simulations open the door to directly performing many-body thermometry in dipolar Rydberg atom arrays. Moreover, our results provide new insights into the experimental data, suggesting the presence of intriguing quasi-equilibrium features, and motivating future studies on the non-equilibrium dynamics of the system.

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Towards realization of long-lived chains of circular Rydberg atoms for quantum simulation

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The dynamics of many-body systems, e.g., large arrays of interacting spin-1/2 particles, is one of the most challenging theoretical problems to solve exactly. Quantum simulations, emulating the evolution of a real system, is a promising approach to overcome this difficulty. Recently, experiments using low angular momentum Rydberg atoms trapped in optical tweezers have shown promising results for simulating systems of up to 100 spins. Despite the long lifetime of Rydberg states on the order of 100s microseconds, the overall lifetime of large arrays of particles reduces significantly, thus limiting simulation to shorter evolution times for larger arrays. Our group's approach is to use atoms in circular Rydberg (cRy) states that are characterized by maximal orbital and magnetic quantum numbers. They exhibit even longer lifetimes on the order of several tens milliseconds and spontaneously decay only to a single lower cRy state. This microwave emission can be inhibited by placing them between millimeter-spaced inhibition capacitor plates. It gives us an exceptionally long lifetime of the order of minutes, which is essential for simulating a long system's dynamics [1]. We are currently building an experimental setup for preparing and trapping long chains of cRy atoms inside an inhibition capacitor in the cryogenic environment. The poster presentation will summarize the conceptual principles, the experimental scheme, the main technical challenges, and the project progress.

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Tree Tensor Networks for quantum many-body systems at finite temperature

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Since a physical system can never be cooled down to absolute zero temperature, a complete description of the physics behind the quantum computing devices has to account for finite temperature effects. However, the finite temperature, i.e. mixed state scenario, represents an additional challenge in comparison to the already computationally demanding zero-temperature quantum many-body simulations. Within the tensor network framework, we develop and implement an efficient Tree Tensor Network based algorithm for computing the finite temperature many-body density matrix. We present the numerical techniques for computing the purity, Von Neumann entropy, Rényi entropies of any order, negativity, and entanglement of formation for the mixed state systems. Our approach is successfully applied to one-dimensional quantum Ising model, and moreover, to the systems of neutral Rydberg atoms trapped in the optical tweezer arrays, representing a physical quantum computing and simulation platform.

QRydDemo - A Rydberg Atom Quantum Computer Demonstrator

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Within the QRydDemo project, our goal is to realize a neutral atom quantum computer setup using strontium Rydberg atoms trapped in optical tweezers. Making use of long natural lifetimes of metastable states in alkaline-earth atoms and extending the possibility for magic wavelength trapping in optical dipole traps, we investigate a novel fine-structure qubit, encoded in the clock state $^3P_0$ and the $^3P_2$ state of the bosonic isotope ^{88}Sr [1]. For this proposed qubit we expect a so-called triple magic wavelength, for which not only both qubit states but also the Rydberg state is "magically" trapped. Moreover, exploiting this feature will allow high-fidelity two-qubit gate realizations via single photon transitions to the Rydberg state and fast single-qubit gates directly implemented via strong Raman transitions between the qubits and the $^3S_1$ state.
Our experimental platform is based on a dynamic, two-dimensional tweezer array of up to 500 qubits, generated by a setup of 20 Acousto-Optical Deflectors (AODs) [2]. This novel approach to tweezer generation extends the connectivity of the platform due to possible shuffling operations during the qubit coherence time. To protect the atoms from environmental effects, the atom array is generated under ultra-high vacuum and protected by an electric field control with ITO coated windows [3].
The experiment hardware is supported by a developed compiler backend tailored specifically to our Rydberg platform. In combination with an already available web-interface this allows emulation and future operation of the quantum computer by public access.

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Nonadiabatic interaction effects in the spectra of ultralong-range Rydberg molecules

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Ultralong-range Rydberg molecules (ULRM) are highly imbalanced bound systems formed via the low-energy scattering of a Rydberg electron with a ground-state atom. We investigate for ^{23}Na the d-state and the energetically close-by trilobite state, exhibiting avoided crossings that lead to the breakdown of the adiabatic Born-Oppenheimer (BO) approximation. We develop a coupled-channel approach to explore the nonadiabatic interaction effects between these electronic states. The resulting spectrum exhibits stark differences in comparison to the BO spectra, such as the existence of above-threshold resonant states without any adiabatic counterparts, and a significant rearrangement of the spectral structure as well as the localization of the eigenstates. Our study motivates the use of ^{23}Na ULRM, as a probe to explore vibronic interaction effects on exaggerated time and length scales

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Cryogenic Strontium Quantum Processor

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With the increasing perfection in the control of quantum mechanical many-body systems, first steps for the realization of simple quantum computers have been made. Various physical systems can serve as a basis for such quantum computers. The most prominent examples are coupled superconducting circuits[1] and trapped ions[2]. Neutral Rydberg atoms in optical tweezers, which saw dramatic technological progress[3, 4] in recent years, offers the opportunity to form another promising platform for quantum computing. This platform unites fundamentally indistinguishable qubits and precise control via light fields with scalability in the size of the qubit register. In our project, we work with fermionic 87Sr. The qubit states are defined on two hyperfine sublevels of the ground state. We aim at the unification of the optical tweezer technology with the carefully designed cryogenic setup at 4K. This will result in a record-breaking long coherence and lifetime of the atoms in the optical tweezer array and form the basis for scalability to large atom numbers. Furthermore, the intensity of black-body radiation is strongly reduced in cryogenic environments. This reduces the unintended coupling between neighboring Rydberg states, a potential source for collective decoherence in a quantum processor. In addition, the cryogenic environment enables the usage of superconducting coils, which offers outstanding passive stability of the magnetic field and thereby increases the qubit coherence.

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Chiral spin liquids in Rydberg models with dipolar exchange interactions

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We investigate the nature of quantum phases arising in chiral interacting Hamiltonians recently realized in Rydberg atom arrays. To this end, we classify all possible fermionic chiral spin liquids with U(1) global symmetry using parton construction on the honeycomb lattice. The corresponding variational wave functions accurately describe the Rydberg many-body ground state at 1/2 and 1/4 particle density. Complementing this analysis with tensor network simulations, we conclude that both particle filling sectors host a spin liquid with the same topological order of a v=1/2 fractional quantum Hall effect. At density 1/2, our results clarify the phase diagram of the model, while at density 1/4, they provide an explicit construction of the ground state wave function with almost unit overlap with the microscopic one. These findings pave the way to the use of parton wave functions to guide the discovery of quantum spin liquids in chiral Rydberg models.

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Rydberg atom array for simulating spin systems

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With properly selected electronic levels, single atoms trapped in optical tweezer arrays are one of the most promising platforms for large-scale spin-1/2 systems simulation, variational quantum eigensolving and quantum computing. The spin states can be selectively read out with fluorescence imaging on the narrow 1S0-3P1 transition, with 99.9% fidelity. Atoms stay in the traps under imaging exposure for over 78 seconds. Here we demonstrate Rabi oscillation and collective Rydberg excitation, via dipole-induced interactions, in defect-free array patterns formed by 88Sr atoms trapped in 813-nm optical tweezers. This long-range interaction provides tunable parameters for studying various condense matter models. In collaboration with Prof. C. Morais Smith's theory team from University of Utrecht, we are preparing to study spin-spin interactions in the Sierpinsky triangle.

Strontium Atoms in Tweezer Arrays for Hybrid Quantum Computing

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Our project has the goal of building a quantum co-processor as part of a hybrid quantum computer that will be tailored to solving problems in quantum chemistry. This will be experimentally realized by trapping strontium-88 atoms in a 2D array of optical tweezers, generated by a spatial light modulator. As qubit states we plan to use the ground $^1S_0$, and clock state $^3P_0$ of the Sr atom. Transitions between these states will be driven by a 698 nm laser and a strong magnetic field. Site selectivity will be achieved with the use of crossed acousto-optic deflectors and may in the future be expanded upon by using a fiber array for parallel qubit addressing. Global excitations to Rydberg states with a 317 nm laser will be used to generate entanglement between the qubits.

On this poster, we will report on the progress we have made so far on building the experimental setup and loading atoms in a blue and red magneto-optical trap. Further, we report on our future plans of using a pulse-based instead of gate-based approach and making our system available online on the Quantum Inspire platform.

Mercury Rydberg molecules

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Due to their unusual energy structure and permanent dipole moments, Rydberg molecules are a topic of recent research interest. In our work, we examine the ultralong-range Rydberg molecules, composed of a Rydberg and a ground-state atom. By far, physicists have mostly focused on molecules built with atoms with one valence electron (like Rb, Cs [1]). Some attempts have been made to calculate Sr [2] and Yb molecules but due to their complexity, the progress has stalled. We construct a complete model to describe the ultralong-range Rydberg molecule containing the Hg atom which has got two valence electrons but luckily can be treated as a single-channel element. We pave the path toward more complex species and encourage possible experimental realizations.

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Probing Hilbert space fragmentation and time crystalline order with Rydberg atoms

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Rydberg atom has emerged as a promising platform for exploring novel many-body phenomena. Previously, we develop a Rydberg dressing scheme that can access the extremely anisotropic regime of the Heisenberg model [1]. Our recent analysis reveals that the model can be mapped exactly onto a modified version of the folded XXZ model, possessing U(1) symmetries of the total magnetization and the domain wall number, while exhibiting the strong Hilbert space fragmentation (HSF). The effective Hamiltonian has distinct time scales for the motion of a magnon and a hole, which allows for a continuous tuning from the integrable regime, to the Krylov-restricted thermal phase, and eventually to the statistical bubble localization region. As a signature of the HSF, our experimental collaborators recently identify the kinetically constrained frozen dynamics and the formation of a long-range magnon bound state in a Rydberg tweezer array setup.

In a different project, we experimentally demonstrate a possible time crystalline order in a driven-dissipative Rydberg gas contained in an atomic vapor cell [2]. We show that the coexistence and competition between distinct Rydberg components can lead to a limit cycle phase featuring persistent oscillating dynamics. The measured undamped autocorrelation function suggests the establishment of a true long-range order, which together with the robustness against temporal noises further supports our realization of a dissipative time crystal.

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Quantum annealing for quantum optimization problems with arbitrary connections in Rydberg atom arrays

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A novel scheme has recently been proposed for encoding optimization problems with arbitrary connections into the Rydberg atom arrays [1]. In this scheme, the (dis)connection between the logical bits is represented by the (Crossing) Crossing-with-edge gadgets. This work focuses on studying the quantum annealing of the encoding scheme. We observe the presence of an avoided level-crossing for the Crossing-with-edge gadgets in certain configurations, where the minimum energy gap decays exponentially. We propose a viable approach to avoid the first-order transition, resulting in only a polynomial overhead in annealing time compared to the original problem. Furthermore, we benchmark the performance on instances that can be mapped to a one-dimensional structure and the scaling of the minimum gap is strongly correlated to the original problem.

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Neutral-Atom Quantum Computing Demonstrator

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MUNIQC-Atoms targets the realization of a neutral-atom quantum processor based on atoms trapped in optical tweezers combined with Rydberg-induced quantum gates. Within 5 years, this demonstrator will be integrated in the HPC systems of LRZ (Leibniz-Rechenzentrum der Bayeri-schen Akademie der Wissenschaften), providing access to the demonstrator with up to 400 qubits. We aim at average gate fidelities of 99.5% on single and two-qubit gates with locally addressable atomic qubits. With this demonstrator, we lay the groundwork to tackle first applications for NISQ quantum computers and to bring Germany and Europe into a leading position in quantum computing and quantum technologies.