Quantum Science with Interacting Arrays of Rydberg Atoms and Molecules

837. WE-Heraeus-Seminar

27 Jul - 01 Aug 2025
at the Physikzentrum Bad Honnef/Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
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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 837. WE-Heraeus-Seminar:

Atomic and molecular systems in optical tweezer arrays foster various applications reaching from quantum optics and quantum metrology through quantum simulation all the way to quantum computing. The great success of this platform is rooted in the near-perfect isolation of the atomic particles from the environment and in the advanced experimental capabilities and theoretical methods, enabling excellent control and detection at the single-particle level. The strong interactions of Rydberg atoms and of polar molecules take a central role in the fundamental aspects and for the 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, including the ability to implement efficient protocols for quantum error correction. New developments in the field of quantum metrology, such as the application of entangled states, are opening novel venues for precision measurements. Given by the high dynamics in this field, new directions are constantly emerging, such as the investigation of architectures combining different atomic species or hybrid systems of atoms and molecules. This ongoing evolution will pave the way for the investigation of ever more complex quantum model systems in the future. This workshop aims to bring together world-leading experts and young aspiring researchers in the field of the quantum science of optical tweezer arrays of interacting Rydberg atoms and molecules. It shall foster the scientific exchange and the strong community spirit in the field. The span of topics is intentionally kept broad to attract contributors from various fields in order to advance new frontiers in the physics of interacting atoms and molecules in tweezer arrays.

Scientific Organizers:

Prof. Dr. Gerhard Birkl	TU Darmstadt, Germany E-Mail: weh-tweezer-arrays@physik.tu-darmstadt.de
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Introduction

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Registration:

Mrs. Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 20:00 h) and Monday morning

Program

Sunday, July 27, 2025

17:00 – 20:00	Registration	
18:30	*BUFFET SUPPER and informal get-together*	
19:30	Scientific organizers	**Opening and Welcome**
19:45	**Discussion**	

Program

Monday, July 28, 2025

07:30	*BREAKFAST*	
08:45 – 09:00	Scientific organizers	**Opening Remarks**
09:00 – 09:45	Rosario González-Férez	**Ultralong-range Rydberg molecules: Rotational hybridization, Rydberg blockade, and resonant energy transfer**
09:45 – 10:30	Sylvain de Léséleuc	**Ultrafast Rydberg experiments with ultracold atoms**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	**Hot Topic Talks**	
	Lukas Sturm	**Scalable Microlens-Based Integration of Rydberg-Interacting Quantum Arrays**
	Einius Pultinevičius	**Long-lived and trapped Circular Rydberg states of alkaline-earth atoms at room-temperature**
11:45 – 12:30	Oscar Herrera Sancho	**A High-Resolution Ion Microscope to Spatially Observe Ion-Rydberg Interactions**
12:30	*LUNCH*	
14:00 – 14:45	Monika Aidelsburger	**State-dependent potentials and clock-sideband cooling with neutral Yb atoms**
14:45 – 15:30	Huanqian Loh	**Hilbert Space Fragmentation in a Rydberg Quantum Simulator**
15:30 – 16:15	Zoe Yan	**New opportunities in quantum simulation with ultrapolar molecules**

Program

Monday, July 28, 2025

16:15 – 16:45	*COFFEE BREAK*	
16:45 – 17:45	Mikhail Lukin	**Exploring quantum computing frontier with programmable neutral atom systems**
17:45 – 18:30	**Hot Topic Talks**	
	David Petrosyan	**Two- and multiqubit quantum gates between distant atoms mediated by a Rydberg excitation antiferromagnet**
	Adrien Bouscal	**A neutral atom array in an optical cavity for quantum computing**
18:30	*DINNER*	
19:30	**Discussion**	

Program

Tuesday, July 29, 2025

07:30	*BREAKFAST*	
08:45 – 09:45	Tommaso Calarco	**Quantum control for atom-based quantum technologies**
09:45 – 10:30	Daniel Ruttley	**Long-lived entanglement of molecules in magic-wavelength optical tweezers**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	**Hot Topic Talks**	
	Daniel Schneider Grün	**Rydberg excitations of single atoms of erbium**
	Etienne Walraven	**Loading molecules… [▮▮▮▮▯ 80%] - Scheme for Deterministic Loading of Laser-Cooled Molecules into Optical Tweezers**
11:45 – 12:30	Matthew Eiles	**Electron-mediated interactions in Rydberg tweezers**
12:30	*LUNCH*	
14:00 – 14:45	Lawrence Cheuk	**Quantum Many-Body Physics with Molecular Tweezer Arrays: From Magnon Dynamics to Spin-Squeezing**
14:45 – 15:30	Lysander Christakis	**New directions for dipolar physics with atoms and molecules in tweezer arrays**
15:30 – 16:15	**Hot Topic Talks**	
	Valentin Walther	**Rydberg Macrodimers: From Polariton Decay to Molecular Interactions**
	Alejandro Saenz	**Confinement-induced resonances: control option or nuisance?**
16:15 – 16:45	*COFFEE BREAK*	
16:45– 18:30	**Poster Session**	
18:30	*DINNER*	
19:30	**Discussion**	

Program

Wednesday, July 30, 2025

07:30	*BREAKFAST*	
08:45 – 09:45	Adam Kaufman	**Programmable optical clocks for quantum-enhanced sensing**
09:45 – 10:30	Guido Pupillo	**Towards efficient quantum error correction with neutral atoms**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 12:00	Antoine Browaeys	**Realization of doped magnets in dipolar Rydberg atom arrays**
12:00 – 12:22	**Hot Topic Talk**	
	Giuliano Giudici	**Steering Rydberg atom arrays: from high-fidelity gate design to many-body state preparation**
12:25	**Conference Photo**	
12:40	*LUNCH*	
14:00 – 14:45	Jaewook Ahn	**Rydberg atom collisions and prospects for flying atomic qubits**
14:45 – 15:30	Servaas Kokkelmans	**Experimental Validation of Control Noise - Fidelity relations in a Neutral Atom Quantum Computer**
15:30 – 16:15	Jonathan Pritchard	**Cryogenic Dual-Species Atom Arrays**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 18:30	**Time for Excursion and Discussion**	
18:30	*HERAEUS DINNER at the Physikzentrum* *(cold and warm buffet, with complimentary drinks)*	
19:30	***Discussion***	

Program

Thursday, July 31, 2025

07:30	*BREAKFAST*	
08:45 – 09:00		**The WEH Foundation**
09:00 – 09:45	Ohad Lib	**Universal Gate Operations and Erasure Conversion in a Metastable Fine-Structure Qubit of Bosonic Strontium-88**
09:45 – 10:30	Michael Fleischhauer	**Many-body dynamics of interacting, dissipative spin systems and the Truncated Wigner Approximation for Spins**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	**Hot Topic Talks**	
	Daniel González-Cuadra	**Observation of string breaking on a (2+1)D Rydberg quantum simulator**
	Riccardo Panza	**Fast number-resolved detection of ytterbum arrays**
11:45 – 12:30	Hans Peter Büchler	**Topological order in symmetric blockade structures**
12:30	*LUNCH*	
14:00 – 14:45	Dieter Jaksch	**Stationary states and dynamical quantum phase transitions on random networks**
14:45 – 15:30	Thomas Pohl	**Quantum continuous time crystals in dissipative Rydberg-atom arrays**
15:30 – 16:15	Christian Gross	**Cluster nucleation dynamics in Rydberg arrays**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 18:30	**Poster Session**	
18:30	*DINNER*	
19:30	**Discussion**	

Program

Friday, August 1, 2025

07:30	*BREAKFAST*	
08:45 – 09:45	Manuel Endres	**Quantum Science with Tweezer Arrays**
09:45 – 10:30	Cindy Regal	**A Cryogenic System for Rydberg Atom Arrays**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	**Hot Topic Talks**	
	Adam Shaw	**Cavity array microscopes for quantum science**
	Ofer Firstenberg	**Quantum Vortices of Photons**
11:45 – 12:00	**Poster Prize**	
12:00 – 12:30	Scientific organizers	**Future Directions & Closing Remarks**
12:30	*LUNCH*	

End of seminar and departure

Posters

Posters

Wojciech Adamczyk	**Two-photon cooling of calcium atoms**
Ivan Ashkarin	**Few-body Förster resonances in Rydberg atoms for quantum gate protocols**
Brice Bakkali-Hassani	**Arrays of long-lived circular Rydberg states of strontium**
Hauke Biss	**Rymax one: A neutral atom quantum processor to solve optimization problems**
Katharina Brechtelsbauer	**Measurement-free quantum error correction optimized for biased noise**
Cristina Cicali	**Fast neutral atom transport and transfer between optical tweezers**
Michelle Chong	**Interfacing a Rydberg atom array with an optical cavity**
Ippei Danshita	**Critical velocity in superfluid states of hardcore Bose-Hubbard model with long-range hopping**
Andre De Oliveira	**Quantum wires and local light shifts for graph optimisation on Rydberg atom arrays**
Marco Di Liberto	**Triplon dynamics in Floquet-driven Rydberg quantum simulators**
Aileen Durst	**Anisotropic and non-additive interactions of a Rydberg impurity in a BEC**
Vladislav Gavryusev	**Optimal control in phase space applied to minimal-time transfer of thermal atoms in optical traps**
Bastien Gély	**New generation Rydberg atom array quantum simulator**
Katja Gosar	**Towards quantum simulation with cesium atomic ensembles in optical tweezers**
Clément Gradziel	**Toward the simulation of the Jaynes-Cummings hamiltonian in blockaded arrays of ultracold atoms**

Posters

Alex Gunning	**Mimicking emergent geometry with real geometry in Rydberg atoms**
Philip Kitson	**Sensing spatially varying electric fields through Rydberg atom networks**
Sridevi Kuriyattil	**Entangled states from sparsely coupled spins for metrology with neutral atoms**
Ilango Maran	**Vibrationally coupled Rydberg atom-ion molecules**
Romain Martin	**Realization of a doped quantum antiferromagnet with a Rydberg tweezer array**
Anastasiia Mashko	**Methods and systems for imaging magnetic fields using Rydberg atom arrays**
Siddhant Midha	**Insights into quantum "radiation" metrology**
Marcel Mittenbühler	**Quantum technology platform beyond 1000 atomic qubits for quantum simulation, computation, metrology, and sensing**
Johannes Mögerle	**PairInteraction v2: An open-source toolkit for fast and accurate calculations of Rydberg interactions**
Kevin Mours	**Local control in a Sr quantum computing demonstrator**
Mark Oehlgrien	**Rydberg-cavity platforms: Quantum spin liquids and locality from all-to-all interactions**
Philip Osterholz	**Quantum nucleation of structured clusters under kinetic constraints**
Riccardo Panza	**Fast number-resolved detection of ytterbum arrays**
Laura Pecorari	**High-rate quantum LDPC codes for long-range-connected neutral atom registers**

Posters

Ana Pérez Barrera	**A new Strontium Rydberg tweezers experiment for the study of lattice gauge theories**
Jonas Rauchfuß	**Quantum computation with neutral ytterbium Rydberg atoms in optical tweezer arrays**
Isabelle Safa	**Building a programmable quantum gas microscope**
Èlia Solé Cardona	**Doppler heating in cold atoms**
Daniil Svirskiy	**Magic wavelength traps for collective Rydberg excitations**
Elias Trapp	**Continuous operation of a coherent 3,000-qubit system**
Stefano Veroni	**Fast entangling gates for Rydberg atoms via resonant dipole-dipole interaction**
Kai Voges	**Developing a hybrid tweezer array of laser-coolable dipolar molecules and Rydberg atoms**
Edgar Vredenbregt	**Experimental validation of the influence of control noise on fidelity**
Karen Wadenpfuhl	**Engineering Rydberg-mediated photon-photon interactions**
Conner Williams	**Towards enhanced loading of a NaCs tweezer array**
Louise Wolswijk	**A new quantum computing platform based on Yb atoms in optical tweezer arrays**
Michelle Wu	**An apparatus for millimeter-wave-mediated quantum gates between Rydberg atoms**
Amin Zamani	**Towards neutral atom quantum computing with trapped Yb-171 atoms**
Zhanchuan Zhang	**Dual-type dual-element atom arrays for quantum information processing**

Abstracts of Lectures

(in alphabetical order)

Rydberg atom collisions and prospects for flying atomic qubits

Jaewook Ahn

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Direct acceleration of neutral particles remains a formidable experimental challenge. Optical tweezers offer a promising solution [1] for experimentally investigating collisions between multiple atoms or molecules, enabling not only controlled atomic collisions but also the development of flying atomic qubits. This optical approach to accelerating neutral particles opens up exciting possibilities not only for fundamental studies but also, in the realm of quantum technology, the development of flying atomic qubits. In this presentation, we will report the latest experimental results of Rydberg atom collisions [2] and discuss the technical prospects and requirements for flyby-based controlled-Z (CZ) gate, where a single atomic release can implement multiple entangling operations. This dynamic approach may open the door to fast, scalable gate operations and enhanced connectivity in neutral atom quantum computing.

References

[1] H. Hwang, A. Byun, J. Park, S. d. Léséleuc, and J. Ahn, Optical tweezers throw and catch single atoms, Optica 10, 401 (2023).
[2] H. Hwang, S. Hwang, J. Ahn, S. Yoshida, and J. Burgdorfer, Impact-parameter selective Rydberg atom collision by optical tweezers, arXiv:2412.06225

State-dependent potentials and clock-sideband cooling with neutral Yb atoms

M. Aidelsburger[1,2,3]

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High-fidelity control and manipulation of neutral atoms in optical lattices and tweezer arrays is essential for applications in quantum computing, simulation, and metrology. In this talk, I will present a new experimental platform for quantum simulation of itinerant systems using fermionic ^{171}Yb in a clock-magic optical lattice. Key features include fast loading of atoms from a MOT into a deep lattice and state-dependent local control using so-called tune-out potentials, where only one of the two clock states experiences a finite AC Stark shift.

A crucial ingredient for our fast-loading scheme is efficient ground-state cooling to ultra-low temperatures. Traditionally, this is achieved via evaporative cooling, which in general however is rather slow. Recently, we developed a chirped sideband cooling technique on the ultranarrow optical clock transition to directly cool both fermionic and bosonic isotopes of ytterbium close to their motional ground state in 2D and 3D clock-magic optical lattices [1]. Our approach achieves average motional excitations as low as $\bar{n} \simeq 0.015$ for fermions in 2D. In 3D, excitations are currently limited to $\bar{n} \simeq 0.15$ due to spatial inhomogeneities in the vertical lattice, which can be mitigated by isolating a single plane.

Combined with our recent results on tune-out potentials for the two clock states [2,3], this platform now brings together several unique capabilities - paving the way for next-generation fermionic quantum simulation in the context of open quantum systems and high-energy physics.

References

[1] R. M. Kroeze, R. A. Villela, E. Zu, T. O. Höhn, M. Aidelsburger, arXiv: 2506.09031 (2025)

[2] T. O. Höhn, R. A. Villela, E. Zu, L. Bezzo, R. M. Kroeze, M. Aidelsburger, arXiv: 2412.14163 (2024)

[3] T. O. Höhn, E. Staub, G. Brochier, N. Darkwah Oppong, M. Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

A neutral atom array in an optical cavity for quantum computing

Balázs Dura-Kovács[1,2,3], Mehmet Öncü[1,2,3],
Jacopo de Santis[1,2,3], Mullai Sampangi[1,2,4], Dimitrios Vasileiadis[1,2,3,4],
Adrien Bouscal[1,2,3], Johannes Zeiher[1,2,3]

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Neutral atoms in optical tweezers arrays have shaped the research frontier in quantum simulation, quantum metrology and quantum computation in recent years. In particular, breakthroughs were achieved in scaling the array sizes, in implementing close to unity fidelity manipulation and in fast, high-fidelity entanglement generation through the coupling to high-lying Rydberg states [1].

In our experiment, we leverage these developments to realize a novel experimental platform aimed at coupling a rubidium atom array to a high-finesse optical resonator [2], with the goal to strongly couple the individual atoms to the cavity mode. We will present our compact and versatile experimental design, our ability to trap and manipulate individual rubidium atoms in optical tweezers inside the resonator, and our progress towards coupling the atoms to the optical mode and exciting them to their Rydberg states. This platform opens new perspectives on a variety of directions, including fast readout and feedback for cyclic error correction in tweezer arrays, remote entanglement generation in or between atom arrays, and the quantum simulation of open-system dynamics.

We finally introduce our plan towards an Ytterbium-Rubidium dual-species array [3]. Harnessing the rich electronic structure of alkaline-earth-like atoms, this array paired with an optical cavity will allow us to implement novel error correction, mitigation, and distributed quantum computing protocols.

References

[1] S. Evered et al., "High-fidelity parallel entangling gates on a neutral-atom quantum computer," Nature, **622**, 268–272 (2023).
[2] E. Deist et al., "Mid-Circuit Cavity Measurement in a Neutral Atom Array," Phys. Rev. Lett. **129**, 203602 (2022)
[3] S. Anand et al., "A dual-species Rydberg array" Nature Physics **20**, 1744–1750 (2024)

Realization of doped magnets in dipolar Rydberg atom arrays

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This talk will present recent experiments where we explore the dynamics of hole in a spin background, implementing a bosonic version of the t-J model usually introduced to describe the properties of doped magnets. To do so, we use the resonant dipole interaction between Rydberg atoms in tweezer arrays and rely on three Rydberg states in each atom to encode the spin and the hole. Varying the ration t/J, we observe in a one dimensional chain the binding of holes and the influence of the dipolar tail of the interaction on the propagation of the holes. Working in a triangular ladder geometry and in a regime where $t \gg J$, we observe the binding of a magnon and hole and explore kinetic frustration in this system.

Topological order in symmetric blockade structures

Tobias F. Maier, Hans Peter Büchler, and Nicolai Lang

Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, 70550 Stuttgart, Germany

The bottom-up design of strongly interacting quantum materials with prescribed ground state properties is a highly nontrivial task, especially if only simple constituents with realistic two-body interactions are available on the microscopic level. Here we study two- and three-dimensional structures of two-level systems that interact via a simple blockade potential in the presence of a coherent coupling between the two states. For such strongly interacting quantum many-body systems, we introduce the concept of blockade graph automorphisms to construct symmetric blockade structures with strong quantum fluctuations that lead to equal-weight superpositions of tailored states. Drawing from these results, we design a quasi-two-dimensional periodic quantum system that – as we show rigorously – features a topological Z2 spin liquid as its ground state. Our construction is based on the implementation of a local symmetry on the microscopic level in a system with only two-body interactions.

References

[1] T.F.Maier, arxiv: 2503.17123 (2025)

Quantum Many-Body Physics with Molecular Tweezer Arrays: From Magnon Dynamics to Spin-Squeezing

Lawrence W. Cheuk[1]

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Molecular tweezer arrays are an emerging platform for quantum science that combines the richness of molecules with the microscopic control of programmable optical tweezer traps. In the past few years, our group and others have significantly advanced the level of quantum control in this platform, establishing the building blocks required for quantum science. These include high-fidelity single molecule detection, high-fidelity state preparation, coherent control of interactions, and deterministic entanglement. These developments have opened the door to practical applications such as quantum simulation of interacting many-body systems, quantum information processing, and quantum-enhanced sensing.

In this talk, I will report recent work where we have entered, for the first time, the quantum many-body regime with molecular tweezer arrays. Using two new capabilities that we have developed - measurement-enhanced quantum state preparation and Floquet engineering, we have realized interacting dipolar quantum spin models with tunable XYZ interactions in mesoscopic 1D chains. I will report experiments exploring magnon dynamics in these systems, which include quantum walks of single spin excitations, dynamics of repulsive magnon bound states, and coherent spin-pair creation and annihilation of pairs. If time permits, I will discuss our latest efforts to use these spin Hamiltonians for quantum-enhanced metrology. Specifically, through dynamical Hamiltonian evolution, we create, for the first time, spin-squeezed states of molecules.

New directions for dipolar physics with atoms and molecules in tweezer arrays

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Quantum many-body systems with dipolar interactions host a variety of exotic phases of matter, such as supersolids and quantum spin liquids. In order to study this physics in the lab, dipolar interactions have been realized in various quantum systems including polar molecules, magnetic atoms and alkali Rydberg atoms. However, to fully explore the phases of dipolar Hamiltonians, it is necessary to scale up to larger system sizes, minimize positional disorder, and prolong the spin coherence time. In this talk, I will present progress on this front via two new experimental systems consisting of alkaline-earth-like Rydberg atoms and ultracold polar molecules. First, I will describe the development of a new ytterbium (Yb) Rydberg tweezer platform for studying dipolar physics. By leveraging the special atomic structure of Yb to trap and manipulate Rydberg states, we envision preparing many-body states such as chiral spin liquids with arrays of thousands of atoms.

In parallel, several experiments have also demonstrated control of dipolar interactions between individual molecules, including the recent demonstration from our group of an iSWAP gate between two NaCs molecules. I will describe a new effort to improve the system size and reduce the entropy of NaCs tweezer arrays. Specifically, we will perform evaporative cooling on small ensembles of NaCs molecules to deterministically prepare an individual molecule in each tweezer of a 2D array. This work paves the way for studying dipolar quantum matter in new regimes, and will allow for a quantitative comparison of decoherence mechanisms, such as spin-motion coupling, between two of the leading platforms.

Ultrafast Rydberg experiments with ultracold atoms

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Rydberg atoms, with their giant electronic orbitals, exhibit dipole-dipole interaction reaching the GHz range at a distance of a micron, allowing 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 and explore this ultrafast Rydberg regime [1,2].

I will introduce the *Rydberg timescale* to position the various limits and opportunities set by atomic physics properties, as well as the technical challenges in reaching them with today's experimental tools. We will then look at how we excite Rydberg atoms as fast as physically possible (~10 picoseconds) by pulsed lasers, non-linear optics and spectral optimization [3]. With the atoms now in the Rydberg states, we will revisit how fast they can interact with each other through long-range dipole-dipole interaction and demonstrate coherent dynamics in the nanosecond timescale. Finally, we will consider how the internal electronic Rydberg dynamics driven by interaction couples coherently to the external motional degrees of freedom (position, momentum). I will show signatures of this effective "spin-motion" coupling on experiments with atoms trapped in optical tweezers and optical lattices [4], and conclude with opportunities offered by control of the motional states with tweezers [5,6].

[1] Y. Chew, T. Tomita, T. P. Mahesh, S. Sugawa, S. de Léséleuc, K. Ohmori, *"Ultrafast energy exchange between two single Rydberg atoms on a nanosecond timescale"*, Nat. Photonics **16**, 724 (2022)

[2] V. Bharti, S. Sugawa, M. Mizoguchi, M. Kunimi, Y. Zhang, S. de Léséleuc, T. Tomita, T. Franz, M. Weidemüller, K. Ohmori, *"Ultrafast Many-Body Dynamics in an Ultracold Rydberg-Excited Atomic Mott Insulator"*, Phys. Rev. Lett. **131**, 123201 (2023)

[3] T.P. Mahesh, T. Matsubara, Y. Chew, T. Tomita, S. de Léséleuc, K. Ohmori, *"Generation of 480 nm picosecond pulses for ultrafast excitation of Rydberg atoms"*, arXiv:2408.02324

[4] V. Bharti, S. Sugawa, M. Kunimi, V. Singh Chauhan, T. P. Mahesh, M. Mizoguchi, T. Matsubara, T. Tomita, S. de Léséleuc, K. Ohmori, *"Strong Spin-Motion Coupling in the Ultrafast Dynamics of Rydberg Atoms"*, Phys. Rev. Lett. **133**, 093405 (2024)

[5] Y. Chew, M. Poitrinal, T. Tomita, S. Kitade, J. Mauricio, K. Ohmori, S. de Léséleuc, *"Ultra-precise holographic optical tweezers array"*, arXiv:2407.20699

[6] H. Hwang, A. Byun, J. Park, S. de Léséleuc, J. Ahn, *"Optical tweezers throw and catch single atoms",* Optica **10**, 401 (2023)

Electron-mediated interactions in Rydberg tweezers

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Atomic tweezer arrays typically leverage long-ranged van der Waals or resonant dipole-dipole interactions between Rydberg atoms for applications in quantum simulation or computing. These interactions couple atoms across the micrometer-scale distances characteristic of tweezer arrays, and can be modified to an extent by exploiting the anisotropy of the dipole-dipole interaction or via Rydberg dressing. Much less explored in this context are the effective interactions between ground-state atoms mediated by a Rydberg electron. These become accessible when the tweezer separation is compatible with the orbit of the Rydberg electron – a prospect facilitated by the huge sizes of Rydberg atoms with large principal quantum numbers. These mediated interactions between ground-state atoms possess a much richer functional form than the power law interactions between distant Rydberg atoms, and can be tuned via the quantum numbers of the Rydberg electron and the positions of the ground-state atoms within the Rydberg orbit.

To illustrate the possibilities of this different approach to coupling atoms in tweezer arrays, I will give three examples utilizing one, two, and many ground-state atoms interacting with a Rydberg atom. I will first report on how long-range diatomic Rb(nS)+Cs(6s) Rydberg molecules bound by this mediated interaction were formed “on demand” in a dual-species Rydberg array [1]. Next, still considering Rydberg *S* states, I will show how a triatomic configuration of atoms, one in a Rydberg state and the other two prepared in different vibrational trap states, can demonstrate vibrational state transfer [2]. Finally, by moving to *N* ground-state atoms within the Rydberg orbit and utilizing the degeneracy of Rydberg states with high angular momentum, I will show how a broad range of effective interactions can be designed. To demonstrate this, we will consider how such a system can be used to study single-particle Anderson localization [3] and topological physics [4].

References

[1] A. Guttridge, T. R. Hepworth, D. K. Ruttley, A. A. T. Durst, M. T. Eiles, and S. L. Cornish Phys. Rev. Lett. **134**, 133401 (2025)
[2] A. Pendse, S. Wüster, M. T. Eiles, and A. Eisfeld New Journal of Physics **27**, 043010 (2025)
[3] M. T. Eiles, C. W. Wächtler, A. Eisfeld, and J. M. Rost Phys. Rev. B **109**, 075422 (2024)
[4] M. T. Eiles, A. Eisfeld, and J. M. Rost Phys. Rev. Research **5**, 033032 (2023)

Quantum Science with Tweezer Arrays

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Optical tweezer arrays have rapidly had a transformative impact on atomic and molecular physics, enabling groundbreaking advances in quantum computing, simulation, and metrology. Their success is rooted in the unique ability to individually control and detect single atoms or molecules with high fidelity and relative simplicity. I will introduce the basic principles behind this versatile approach and highlight recent results from our laboratory. These include quantum simulations that challenge the capabilities of classical computers and novel results in connection with lattice gauge theories, hybrid approaches that integrate quantum computing and atomic clock technologies, and scalable control of more than 6,000 atomic qubits.

Quantum Vortices of Photons

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Imagine pulling a plate across the surface of a tranquil water pool, creating a mesmerizing trail of a vortex and antivortex. In optics, vortices materialize as phase twists of the electromagnetic field. While traditionally optical vortices arise from interactions between light and matter, we discovered an extreme regime of optical nonlinearity where quantum vortices – phase dislocations in the few-photon wavefunction – form due to effective, strong interactions between the photons [1]. These interactions are realized in a 'quantum nonlinear optical medium' based on ultracold Rydberg atoms. Analogous to the water pushed by the plate, the excess phase accumulating due to the photon-photon interaction gives rise to pairs of quantum vortices, vortex lines, and rings, within the photonic wavefunction. The vortex rings are warped due to warping of the underlying dispersion [2]. The 'conditional' phase flip enclosed by the vortices can be used for deterministic quantum logic operations. Counter-propagating photons, in a configuration suitable for quantum gates, exhibit even longer-range, richer interactions [3].

1. Drori *et al.*, Quantum vortices of strongly interacting photons, *Science* 381, 193-198 (2023)
2. Das *et al.*, Multiband dispersion and warped vortices of strongly-interacting photons, *arXiv*:2502.11553 (2025)
3. Das *et al*., Quantum nonlinear optics with counter-propagating photons, *arXiv*:2506.01124 (2025)

Many-body dynamics of interacting, dissipative spin systems and the Truncated Wigner Approximation for Spins

Michael Fleischhauer

The many-body dynamics of (dissipative) quantum spin systems is of key importance in many areas of physics and technology ranging from (dissipative) and non-equilibrium phase transitions to collective radiative interactions such as superradiance. Its exact numerical treatment is however extremely challenging, being restricted either to small systems where the time evolution of the full many-body density matrix can be simulated or to the classical limit of strong dephasing, which can be tackled by Monte Carlo methods. In this talk I discuss a semiclassical approach to this problem, termed truncated Wigner approximation (TWA) for spins, that allows to describe the coherent and dissipative many-body dynamics while taking into account lowest-order quantum effects. It is an extension of the discrete TWA, originally developed for unitarily coupled spins [1], to include dissipative [2] and collective [3] spin processes resulting in a set of semiclassical, numerically inexpensive stochastic differential equations. I discuss the application of this method to the superradiant decay of a spatially extended ensemble of atoms including the simulation of multi-time correlations, the absorbing-state phase transition of a coherently driven Rydberg lattice gas under facilitation conditions and the simulation of quantum annealing protocols.

[1] J. Schachenmayer, A. Pikovski, and A. M. Rey,
Many-body quantum spin dynamics with monte carlo trajectories on a discrete phase space
Phys. Rev. X **5**, 011022 (2015).

[2] Christopher D. Mink, David Petrosyan, and Michael Fleischhauer
Hybrid discrete-continuous truncated Wigner approximation for driven, dissipative spin systems
Phys. Rev. Res. **4**, 043136 (2022)

[3] Christopher D. Mink and Michael Fleischhauer
Collective Radiative Interactions in the Discrete Truncated Wigner Approximation
SciPost Physics **15**, 233 (2023)

Steering Rydberg atom arrays: from high-fidelity gate design to many-body state preparation

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Accurate and coherent control of neutral atom arrays is essential for both implementing high-fidelity quantum gates and preparing entangled many-body quantum states. We first introduce a novel CZ gate protocol that leverages optimal control techniques to challenge the current state of the art in gate performance. We then show how the same methods scale to systems of several qubits, enabling the design of control schemes for complex many-body dynamics. In particular, we present an "adiabatic echo protocol" that significantly enhances robustness in the preparation of strongly correlated many-body states. We apply this protocol to the generation of Greenberger-Horne-Zeilinger states and quantum spin liquids in Rydberg atom arrays, and demonstrate its generality across a broad class of interacting quantum systems.

References

[1] G. Giudici, S. Veroni, G. Giudice, H. Pichler, J. Zeiher, arXiv:2411.05073 (to appear in PRX Quantum)

[2] Z. Zeng*, G. Giudici*, A. Senoo, A. Baumgärtner, A. M. Kaufman, H. Pichler, arXiv:2506.12138

Observation of string breaking on a (2+1)D Rydberg quantum simulator

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Lattice gauge theories (LGTs) describe a broad range of phenomena in condensed matter and particle physics. A prominent example is confinement, responsible for bounding quarks inside hadrons such as protons or neutrons. When quark-antiquark pairs are separated, the energy stored in the string of gluon fields connecting them grows linearly with their distance, until there is enough energy to create new pairs from the vacuum and break the string. While such phenomena are ubiquitous in LGTs, simulating the resulting dynamics is a challenging task. In this talk, I will report the observation of string breaking in synthetic quantum matter using a programmable quantum simulator based on neutral atom arrays [1]. I will first show how a (2+1)D LGT with dynamical matter can be efficiently implemented when the atoms are placed on a Kagome geometry, with a local U(1) symmetry emerging from the Rydberg blockade, while long-range Rydberg interactions naturally give rise to a linear confining potential between pairs of charges. In the experiment, we probe string breaking in equilibrium by adiabatically preparing the ground state of the atom array in the presence of defects, distinguishing regions within the confined phase dominated by fluctuating strings or by broken string configurations. Finally, by harnessing local control over the atomic detuning, we quench string states and observe string breaking dynamics exhibiting a many-body resonance phenomenon. As an outlook, I will present a roadmap to further explore phenomena in high-energy physics using programmable quantum simulators.

References

[1] Nature 642, 321–326 (2025)

Ultralong-range Rydberg molecules: Rotational hybridization, Rydberg blockade, and resonant energy transfer.

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Rydberg atoms also form exotic ultralong-range molecules when combined with ground-state atoms [1,2], ions [3], or polar molecules [4,5], which inherit their exciting properties. In this talk, we will explore the interaction, via anisotropic scattering, of a polar molecule with a Rydberg atom creating a polyatomic Rydberg molecule [4,5,6]. The polar diatomic molecule is allowed to rotate in the electric fields generated by the Rydberg electron and core. As a consequence, its rotational structure is significantly affected, and the diatomic molecule becomes oriented and aligned with respect the ionic core [7,8]. We will also discuss the first experimental demonstration of the Rydberg blockade due to this charge-dipole interaction between a Rb atom and a RbCs molecule [8]. Finally, we will analyze the resonant energy transfer between two Rydberg levels in helium due to a low-temperature collisions with polar molecules [10].

[1] C.H. Greene, et al, Phys. Rev. Lett. **85**, 2458 (2000).
[2] V. Bendkowsky, et al, Phys. Rev. Lett. **105**, 163201 (2010).
[3] N. Zuber, et al, Nature **605**, 453–456 (2022).
[4] S.T. Rittenhouse and H.R. Sadeghpour, Phys. Rev. Lett. **104**, 243002 (2010).
[5] R. González-Férez, et al, New J. Phys. **17**, 013021 (2015).
[6] R. González-Férez, et al, Phys. Rev. Lett. **126**, 043401 (2021).
[7] R. González-Férez, et al, J. Phys. B: At. Mol. Opt. Phys. **53**, 074002 (2020).
[8] D.Mellado-Alcedo, et al, Phys. Rev. A **110**, 013314 (2024).
[9] A. Guttridge, et al, Phys. Rev. Lett. **131**, 013401 (2023).
[10] J. Zou et al, in preparation (2025).

Cluster nucleation dynamics in Rydberg arrays

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Strong Rydberg interactions, dominating all other relevant energy scales in a quantum system, are at the heart of the Rydberg blockade. But they can equally well be used to realize an anti-blockade scenario, in which the dynamics are conditioned on the presence of seed atoms in the Rydberg state. In many-body systems, this results in strong kinetic constraints. Here we report on a microscopic study of the dynamics of cluster growth around seed atoms in one and two dimensions. We observe fast saturation and oscillatory behavior of the cluster size in 1D and highly structured growth to large sizes in 2D. The 2D clusters are restricted in their shape, a hallmark of the constraint dynamics, which is predicted to lead to slow thermalization and glass-like dynamics on longer timescales.

A High-Resolution Ion Microscope to Spatially Observe Ion-Rydberg Interactions

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Here, we present the findings of our recent studies on ion-Rydberg atom interactions conducted in the ultracold regime using a high-resolution ion microscope. This experimental apparatus offers temporal and spatial imaging of charged particles with a resolution of at least 200 nm[1]. While neutral ultralong-range Rydberg molecules have been studied extensively in the past, our group has recently observed for the first time charged molecular dimers, consisting of an ion bound to a Rydberg state via a novel flipping-dipole binding mechanism[2]. This discovery enabled *in-situ* imaging of triggered vibrational dynamics[3] in these dimer systems and opened a new domain of ultracold Rydberg chemistry.

Systems combining ions and Rydberg atoms offer various interesting phenomena for research. Already simple pair states consisting of one ion and one Rydberg atom allow for the observation of complex collisional dynamics on steep attractive potential energy curves featuring multiple avoided crossings with adjacent states. Those can lead to a drastic speed-up of the collision process[4]. Avoided crossings can also give rise to molecular bound states by forming potential wells. These bound states between an ion and a Rydberg atom feature huge bond lengths of several micrometers, enabling the direct observation of vibrational dynamics. Further, this binding mechanism is not limited to diatomic molecules but can be extended to polyatomic molecules, for which we expect interactions that are even more intricate. Molecules consisting of three atoms are by nature much richer in their physics compared to dimers, which makes them more interesting, yet also more complicated to study. In particular, for a bound state between two Rydberg atoms and one ion, we therefore predict a rich interaction potential that comprises the interaction between induced dipoles, ion-Rydberg atom interactions, and the Rydberg blockade effect.

[1]C. Veit, N. Zuber, O. A. Herrera-Sancho, V. S. V. Anasuri, T. Schmidt, F. Meinert, R. Löw, and T. Pfau, *Phys. Rev. X* **11**, 011036 (2021).
[2]N. Zuber, V. S. Anasuri, M. Berngruber, Y. Q. Zou, F. Meinert, R. Löw, and T. Pfau, *Nature* **605**, 7910 (2022).
[3]Y. Q. Zou, M. Berngruber, V. S. Anasuri, N. Zuber, F. Meinert, R. Löw, and T. Pfau, *Phys. Rev. Lett.* **130**, 023002 (2023).
[4]M. Berngruber, D. J. Bosworth, O. A. Herrera-Sancho, V. S. Anasuri, N. Zuber, F. Hummel, J. Krauter, F. Meinert, R. Löw, and T. Pfau, *Phys. Rev. Lett.* **133**, 083001 (2024).

Stationary states and dynamical quantum phase transitions on random networks

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The rapid advancement of technology for trapping and manipulating ultracold neutral atoms enables the creation of controlled long-range atomic interactions by exciting them to high-lying Rydberg states. This allows the realization and study of quantum many-body systems whose interactions are no longer limited by geometry. This motivates the study of quantum spin systems whose interactions are described by generic networks.

Specifically, I will discuss stationary states and two types of dynamical quantum phase transitions (DQPTs) in the transverse field Ising model whose interactions are described by edges of Erdős-Rényi networks of size N. These networks consist of vertices connected randomly with probability $0 < p \leq 1$.

For stationary states [1], we find that, with certainty in the thermodynamic limit, such systems behave like a single collective spin. We thus understand the emergence of complex many-body physics as dependent on exceptional, geometrically constrained structures such as the low-dimensional, regular ones. Within the space of dense graphs, we identify exceptions via their inhomogeneity and observe how complexity is heralded in these systems by entanglement and highly non-uniform correlation functions.

We also compare the characteristics of the DQPTs for $p < 1$ against the fully connected network $p = 1$ [2]. For DQPTs defined by an order parameter, the critical point remains unchanged for all p. For DQPTs defined by the rate function of the Loschmidt echo, we find that this rate function deviates from the $p = 1$ limit near vanishing points of the overlap with the initial state, while the critical point remains independent for all p. Our analysis suggests that this divergence arises from persistent non-trivial global many-body correlations absent in the $p = 1$ limit.

References

[1] J. Tindall, A. Searle, A. Alhajri, D. Jaksch, *Quantum physics in connected worlds*, Nature Communications volume **13**, 7445 (2022).

[2] Tomohiro Hashizume, Felix Herbort, Joseph Tindall, Dieter Jaksch, *Dynamical quantum phase transitions on random networks*, New J. Phys. **27** 064506 (2025)

Programmable optical clocks for quantum-enhanced sensing

Adam M. Kaufman

Optical atomic clocks based on transitions in atoms and ions continue to be at the frontier of time and frequency metrology. The precision of such a clock depends on the number of atoms that can be interrogated in parallel, as well as the relative coherence time of the atoms with the oscillator that is being stabilized to the atoms. When using many atoms, multi-particle entanglement can also be used to improve the precision of the clock. I will describe our work in this area, using an array of strontium atoms that are controlled with single-particle resolution via a tweezer array and entangled using Rydberg interactions. I will describe one experiment where we demonstrate a new multi-qubit gate protocol to create so-called “cascaded GHZ states” for enhanced sensing with a large dynamic range, as well as recent experiments using more sophisticated circuits.

Experimental Validation of Control Noise - Fidelity relations in a Neutral Atom Quantum Computer

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We experimentally validate theoretical relationships between control noise and qubit fidelity in a rubidium-85 (Rb-85) based neutral atom quantum computer with atoms filling 100 optical tweezers, cooled down to a temperature of 15 μK. The precise control capabilities of this system allow us to impose noisy control signals onto the qubits with a temporal resolution of 4 ns. We systematically analyze the impact of various noise profiles on the fidelity of quantum states. The measured fidelities are compared against dynamic simulations of the stochasic Schrödinger equation [1]. Our results show good agreement between the qubit readout data and the prediction from our theoretical modeling that involve both the qubit gate operations and noise profiles. Our results lead to a larger robustness of the Rb-85 based qubits under realistic operational conditions and more generally to better optimizing control protocols in neutral atom tweezer arrays.

[1] R. J. P. T. de Keijzer, L. Y. Visser, O. Tse, and S. J. J. M. F. Kokkelmans, Qubit fidelity distribution under stochastic schrödinger equations driven by classical noise, Phys. Rev. Res. 7, 023063 (2025).

Universal Gate Operations and Erasure Conversion in a Metastable Fine-Structure Qubit of Bosonic Strontium-88

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The choice of qubit encoding, along with the associated error model, is crucial for determining the qubit-overhead required for quantum error correction. Biased errors, and in particular leakage errors out of the qubit manifold, have been shown to be beneficial for quantum error correction. To this end, ”erasure qubits", where leakage errors can be detected mid-circuit, have been demonstrated in metastable nuclear qubits in neutral atoms [1], and have since been adopted by other platforms.

In this talk, I will describe efforts towards realizing a 17 THz fine-structure qubit encoded in the $3P_0$ and $3P_2$ clock states of strontium-88 [2-4]. I will start by reviewing experimental results on the triple-magic trapping, qubit-coherence, state preparation, and state-resolved detection of the fine-structure qubit [4, 5]. I will then focus on our realization and characterization of a universal set of gates for the fine-structure qubits, showcasing the benefits of erasure conversion and state-resolved detection for gate and Bell-state fidelities [5]. Finally, I will discuss perspectives and preliminary results on the coherent moving of the fine-structure qubit.

References

[1] S. Ma, G. Liu, P. Peng, B. Zhang, S. Jandura, J. Claes, A. P. Burgers, G. Pupillo, S. Puri, and J. D. Thompson, Nature 622, 279 (2023).

[2] G. Unnikrishnan, P. Ilzhofer, A. Scholz, C. Holzl,A. Gotzelmann, R. K. Gupta, J. Zhao, J. Krauter, S. Weber, N. Makki, H. P. Buchler, T. Pfau, and F. Meinert, Phys. Rev. Lett. 132, 150606 (2024).

[3] S. Pucher, V. Kl¨usener, F. Spriestersbach, J. Geiger, A. Schindewolf, I. Bloch, and S. Blatt, Phys. Rev. Lett. 132, 150605 (2024).

[4] M. Ammenwerth, H. Timme, F. Gyger, R. Tao, I. Bloch, and J. Zeiher, arXiv:2411.02869.

[5] R. Tao, O. Lib, F. Gyger, H. Timme, M. Ammenwerth, I. Bloch, and J. Zeiher, in preparation

Hilbert Space Fragmentation in a Rydberg Quantum Simulator

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Hilbert space fragmentation, where the Hilbert space has been shattered into exponentially many disconnected subspaces, can host rich dynamics due to the diverse set of available subspaces. In this talk, I will present our insights on realizing a broad class of Hamiltonians with Hilbert space fragmentation using facilitated Rydberg atom arrays. I will then report on a few different types of novel non-equilibrium dynamics observed with our fragmented models.

First, we uncover a general version of quantum many-body scarring starting from Z_{2k}-ordered initial states. Second, we observe that quantum thermalization proceeds in a way that is restricted to a particular Hilbert space fragment. Notably, thermalization between states belonging to different subspaces is precluded, even when these states have the same energy, defying expectations from the eigenstate thermalization hypothesis [1].

Finally, we present the first experimental signatures of statistical localization - a notion that challenges the conventional expectation that nonlocal conservation laws do not impede thermalization locally. Our observations of statistical localization take place in a setting where conservation laws play a significant role: a quantum simulator of lattice gauge theory (LGT). We realize a novel constrained LGT model with our facilitated Rydberg atom array, where atoms mediate the dynamics of electric charge clusters whose nonlocal pattern of net charges remains invariant. We find that, as a result of strong Hilbert space fragmentation, the expectation values of all conserved quantities remain locally distributed in typical quantum states, even though they are described by nonlocal string-like operators [2]. Our work opens the door to high-energy explorations of cluster dynamics and low-energy studies of strong zero modes that persist in infinite-temperature topological systems.

[1] L. Zhao, P. R. Datla, W. Tian, M. M. Aliyu, and H. Loh, Physical Review X, 15, 011035 (2025)
[2] P. R. Datla, L. Zhao, W. W. Ho, N. Klco, and H. Loh, arXiv:2505.18143.

Exploring quantum computing frontier with programmable neutral atom systems

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We will discuss recent advances in realizing programmable quantum systems using neutral atom arrays excited into Rydberg states. These systems allow control over several hundred qubits in two dimensions and the exploration of quantum algorithms with encoded logical qubits and quantum error correction techniques. Recent experiments using neutral atom systems have redefined this exciting scientific frontier of quantum computing. They herald the advent of early error-corrected quantum computation and chart a path towards large-scale logical processors. Examples of emerging scientific directions, in areas ranging from architectural mechanisms for universal fault tolerant quantum processing to many-body physics will be discussed.
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Fast number-resolved detection of ytterbium arrays

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In this contribution [1], I will report fast and low-loss single-atom imaging in optical tweezers without active cooling, enabled by the favorable properties of ytterbium. Collecting fluorescence over microsecond timescales, we reach single-atom discrimination fidelities above 99.9% and single-shot survival probabilities above 99.5%. Through interleaved recooling pulses, as short as a few hundred microseconds for atoms in magic traps, we perform tens of consecutive detections with constant atom-retention probability per image, an essential step toward fast atom re-use in tweezer-based processors and clocks. Our scheme does not induce parity projection in multiply-occupied traps, enabling number-resolved single-shot detection of several atoms per site. This allows us to study the near-deterministic preparation of single atoms in tweezers driven by blue-detuned light-assisted collisions: our experiments will provide a benchmark for future theoretical efforts aimed at finding optimal regimes for loading efficiency and speed. Moreover, the near-diffraction-limited spatial resolution of our low-loss imaging enables number-resolved microscopy in dense arrays, opening the way to direct site-occupancy readout in optical lattices for density fluctuation and correlation measurements in quantum simulators, without necessitating dynamical adjustment of atom-spacing. These results position fast in-trap imaging as a compelling approach for atom detection in quantum simulation, metrology and computing platforms.

References

[1] A. M. Falconi *et al*, arXiv preprint arXiv:2507.01011 (2025).

Two- and multiqubit quantum gates between distant atoms mediated by a Rydberg excitation antiferromagnet

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Neutral atoms in arrays of microtraps excited by lasers to strongly interacting Rydberg states represent a highly versatile system for quantum simulations of many-body physics and quantum information processing. Using frequency-chirped laser pulses, the atoms can be transferred to antiferromagnetic-like states of Rydberg excitations, and the preparation fidelity of such states can be accurately estimated using an effective Landau-Zener theory for the adiabatic ground and first excited states of the interacting many-body system [1]. Based on this protocol, we developed an efficient method to realize quantum gates between distant atomic qubits connected by an array of atoms that play the role of a quantum bus [2]. Upon exciting and de-exciting the atoms in the array under the blockage of nearest neighbors, depending on the state of the qubits, the system acquires a conditional geometric π-phase, while the dynamical phase cancels exactly, even when the atomic positions are disordered but nearly frozen in time. We have explored both adiabatic transfer with smooth pulses and non-adiabatic transfer using optimized pulses leading to faster gates with higher fidelities. The same protocol can be adapted to implement multiqubit gates with atoms arranged in star-graph configurations, where the intermediate state of Rydberg excitations corresponds to the solution of the maximum independent set problem for the Ising model.

References

[1] A. F. Tzortzakakis et al., *Phys. Rev. A* **106**, 023513 (2022)

[2] G. Doultsinos, D. Petrosyan, *Phys. Rev. Research* **7**, 023246 (2025)

Quantum continuous time crystals in dissipative Rydberg-atom arrays

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Continuous time crystals, i.e., nonequilibrium phases with a spontaneously broken continuous time-translational symmetry, have been studied and recently observed in the long-time dynamics of different open quantum systems. In particular, experimental studies of strongly interacting thermal Rydberg gases have established that continuous time crystals (CTC) can emerge under the simultaneous optical driving of more than a single interacting Rydberg state [1].

Motivated by these results, we discuss in this talk the dynamics in lattices of interacting Rydberg atoms, under optical two-photon driving with a standard three-level ladder configuration. While the emergence of continuous time-crystal phases in open quantum system as typically based on an underlying mean-field phenomenology, we focus here on their formation under conditions that do not a priory justify a simplified meanfield treatment [2]. Using complementary numerical methods we find two distinct time-crystal phases that cannot be described within mean-field theory. Remarkably, one of these quantum continuous time crystals (qCTCs) emerges only in the presence of quantum fluctuations. Our findings extend explorations of continuous time-translational symmetry breaking in dissipative systems beyond the classical phenomenology of periodic orbits in a low-dimensional nonlinear system. Possible experiments to observe the predicted qCTC phases in tweezer arrays of neutral atoms are also discussed.

References

[1] X. Wu, Z. Wang, F. Yang et al., Dissipative time crystal in a strongly interacting Rydberg gas, Nature Physics 20, 1389 (2024).

[2] F. Russo and T. Pohl, Quantum Dissipative Continuous Time Crystals, arXiv:2503.16141 (2025).

Cryogenic Dual-Species Atom Arrays

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Neutral atom arrays have emerged as a powerful platform for quantum computing due to the intrinsic scability and versatility for performing both high fidelity digital gate operations and analogue quantum simulation and optimisation. Already these features have enabled first demonstrations of logical qubit encodings and error correction, as well as implementations of systems trapping >1000 atoms.

For scaling to even larger system sizes for realising fault-tolerant operation, current barriers include the finite vacuum lifetimes for room-temperature systems, and cross-talk from readout using a single atomic species. To overcome these issues we have developed a new cryogenic, dual species platform for creating arrays of Rb and Cs atoms. In this talk we will present recent progress demonstrating trapping within a 7 K environment, and outline proposals for implementing high-fidelity inter-species gate operations using d-state Förster resonances optimised to enable multi-qubit gates [1]. This approach faciltiates a new parallel-qubit readout protocol that leverages a space-time tradeoff to accelerate mid-circuit measurement without requiring cavities or atomic ensembles [2], addressing another critical barrier to realising fast cycle times in error-corrected atomic systems.

References

[1] P. Ireland *et al.*, Phys. Rev. Research **6**, 013293 (2024)
[2] C. Corlett *et al.*, PRL **134**, 080801 (2025)

Long-lived and trapped Circular Rydberg states of alkaline-earth atoms at room-temperature

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Highly excited Rydberg atoms feature long-range dipolar interactions, which make them favourable in the use for quantum simulation and computation with neutral atoms. However, usual Rydberg excitations at low orbital momentum come with fundamental restrictions. Spontaneous decay limits the coherence time and trapping requirements are challenging.
To overcome these caveats, we are working towards a quantum simulator based on circular Rydberg states (CRS) of neutral $^{88}\mathrm{Sr}$ atoms. Those states at maximum orbital momentum feature only a handful of decay channels which can be suppressed using a resonator made from indium tin oxide (ITO) coated glass plates. This allows the enhancement of the black-body radiation limited lifetime to the millisecond range without use of cryogenics. We explore this effect in our field control structure, and to this end probe CRS at principle quantum numbers of up to 101 via microwave-control. For those Rydberg states, we present measured lifetimes reaching the 10 ms threshold.
Measurements at such timescales further require trapping, which is enabled by the second valence electron of strontium for Gaussian tweezers. By initial preparation in a long-lived CRS, we show trapping times above 100 ms for high orbital momentum states. The low overlap of the ionic core with the circular wavefunction further allows autoionization-free excitations, which is demonstrated by probing state-dependent interactions with the Rydberg electron.

References

[1] C. Hölzl et al., Physical Review X **14**, 021024 (2024).

[2] F. Meinert et al., Physical Review Research **2**, 023192 (2020).

[3] M. Wirth et al., Physical Review Letters **133**, 123403 (2024).

Towards efficient quantum error correction with neutral atoms

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Neutral atoms have emerged as a leading platform for quantum simulation and computation. As the field advances toward scalable, fault-tolerant quantum computing, robust quantum error correction becomes increasingly important. In this talk, we present an architecture for implementing efficient quantum error correction using a class of quantum Low-Density Parity-Check (LDPC) codes, which are compatible with near-term experimental capabilities using Rydberg atom arrays. We discuss scenarios in which these LDPC codes outperform the conventional surface code, particularly in regimes dominated by erasure errors. Under such conditions, quantum LDPC codes exhibit high error thresholds and significant logical error suppression, making them a compelling alternative for experimentally feasible quantum error correction.

A Cryogenic System for Rydberg Atom Arrays

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I discuss experiments with an optical tweezer array of ^{87}Rb atoms housed in an cryogenic environment with high numerical aperture optical access. We demonstrate a 3000-s atom-trap lifetime, which enables us to optimize and measure losses at the 10^{-4} level that arise during imaging and cooling, which are important to array rearrangement. We perform both ground-state qubit manipulation with an integrated microwave antenna and two-photon coherent Rydberg control, with the local electric field tuned to zero via integrated electrodes. We anticipate that the reduced blackbody radiation at the atoms from the cryogenic environment, combined with electrical shielding, should decrease the rate of undesired transitions to nearby strongly interacting Rydberg states, which cause many-body loss and impede Rydberg gates. This low-vibration, high-optical-access cryogenic platform can be used with a wide range of optically trapped arrays of atomic or molecular species.

Long-lived entanglement of molecules in magic-wavelength optical tweezers

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Ultracold polar molecules are a promising platform for quantum science and new quantum technologies. Their rich internal structures are ideal for densely storing quantum information and their long-range interactions provide a mechanism for information transfer. However, these properties make molecules highly sensitive to their environment, affecting their coherence and utility in some quantum-science applications.

Here, we show how these problems can be overcome by preparing molecules in an exceptionally controlled environment. We assemble individually trapped ultracold RbCs molecules [1] and transfer them into magic-wavelength optical tweezers. We encode information in the molecular rotational levels and achieve multisecond coherence times [2]. This long-lived coherence is simultaneously realisable for many rotational transitions, which we exploit to encode spin-1 dynamics in the molecules' rotational structure. Using this encoding, we perform quantum multiparameter estimation with a generalised Ramsey sequence to precisely measure the energies of rotational transitions.

In this pristine environment, we can resolve and exploit hertz-scale dipolar interactions between pairs of molecules in order to entangle them [3]. We entangle molecules using both spin-exchange interactions and direct microwave excitation and prepare two-molecule Bell states with fidelity $0.924^{+0.013}_{-0.016}$. This fidelity is primarily limited by leakage errors. In our experimental platform, we can detect and correct for these errors to achieve a corrected entanglement fidelity $0.976^{+0.014}_{-0.016}$. The second-scale entanglement lifetimes are limited solely by these errors, and we show how the entangled pairs of molecules can be used as quantum-enhanced sensors of local and global perturbations.

The extension of precise quantum control to complex molecular systems will enable their additional degrees of freedom to be exploited across many domains of quantum science. In particular, long-lived molecular entanglement unlocks opportunities for research in quantum-enhanced metrology, ultracold chemistry, and the use of rotational states in quantum simulation, quantum computation, and as quantum memories.

References

[1] D. K. Ruttley, A. Guttridge, T. R. Hepworth, and S. L. Cornish, *PRX Quantum* **5**, 020333 (2024).

[2] T. R. Hepworth, D. K. Ruttley, F. von Gierke, P. D. Gregory, A. Guttridge, and S. L. Cornish, arXiv:2412.15088 (2024).

[3] D. K. Ruttley, T. R. Hepworth, A. Guttridge, and S. L. Cornish, *Nature* **637**, 827 (2025).

Confinement-induced resonances in trapped-particle systems: control knob or nuisance?

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In most (envisioned) quantum-technology applications of ultracold atomic or molecular gases the particles are trapped, an example being Rydberg atoms in optical tweezer arrays. Especially in those cases in which the (effective) interaction length between the particles becomes comparable to the trap length, the interplay between the two interactions cannot be neglected. A striking example is the occurrence of so-called confinement-induced resonances (CIR) that come in two flavors. The first proposed (elastic) CIR (ECIR) occurs only in reduced, quasi-one or quasi-two dimensional geometries. These ECIR are the result of a modified effective inter-particle interaction due to the confinement and can be understood considering relative motion only. On the contrary, the so-called inelastic CIRs (ICIR) are due to a coupling of center-of-mass and relative motion and allow, e.g., for coherent molecule formation (or breaking) by transferring the binding energy into center-of-mass excitation [1,2]. ICIRs are not restricted to reduced dimensionality for which they were found initially, but have recently also been observed experimentally in a three-dimensional lattice [3]. Interestingly, ICIRs can also occur between particles located at neighbor lattice sites, i.e. they can be tunnel induced, as was recently also experimentally demonstrated [4]. Noteworthy, ICIRs are a universal phenomenon as they can occur, e.g., also in quantum dots where they may serve as single-photon-on-demand sources. If the particles interact also via dipolar forces, the resonance position can be tuned by external fields. In fact, as the occurrence depends only on the existence of a coupling between the center-of-mass and the relative motion degrees of freedom, ICIRs are only absent for example in a perfect harmonic trap, but even then only if the particles have identical masses and are in the same state (in order to experience the same trap potential). In view of quantum-technology applications of trapped ultracold atoms, it is thus mandatory to have a complete knowledge about the CIRs, since they may either be used as a control knob, or they may be a nuisance as they may lead to unexpected behavior during as experimental parameters are tuned. Besides providing an overview over the physics especially of ICIRs, some very recent results will be shown.

References

[1] S. Sala, P.-I. Schneider, and A. Saenz, Phys. Rev. Lett. **109**, 073201 (2012)
[2] S. Sala, G. Zürn, T. Lompe, A. N. Wenz, S. Murmann, F. Serwane, S. Jochim, A. Saenz, Phys. Rev. Lett. **110**, 203202 (2013)
[3] D. Capecchi, C. Cantillano, M. J. Mark, F. Meinert, A. Schindewolf, M. Landini, A. Saenz, F. Revuelta, H.-C. Nägerl, Phys. Rev. Lett. **131**, 213002 (2023)
[4] Y. K. Lee, H. Lin. W. Ketterle, Phys. Rev. Lett. **131**, 213001 (2023)

Rydberg excitations of single atoms of erbium

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Neutral atoms in optical tweezers offer great promise as a platform for quantum simulation and computation, with the ability to implement arbitrary geometries, dynamical reconfiguration and controllable long-range coupling via Rydberg-mediated interactions [1,2]. Recently, paradigms going beyond the simple single-electron atom have emerged [3,4]. A relevant, yet little-explored, case is one of sub-merged-shell lanthanides, such as erbium and dysprosium [5,6,7]. Their many valence electrons reflect an unprecedented richness of accessible optical transitions, anisotropic atom-light interaction, and large-orbital momentum states.

The talk will present our recent progress in creating and studying for the first time a tweezer platform of erbium atoms [7,8]. This includes achieving the single-atom regime via light-assisted collisions, the study of differential light shift, and cooling mechanisms. Finally, I will present our latest results on Rydberg excitations of erbium, including the spectroscopical mapping of 550 Rydberg states, measurements of the Rabi frequencies via the Autler-Townes Splitting, and coherent preparation schemes.

References

[1] A.M. Kaufman and K.-K. Ni, Nature Physics **17**, 1324-1333 (2021).
[2] A. Browayes and T. Lahaye, Nature Physics **16**, 132-142 (2020).
[3] M.A. Norcia, A.W. Young, and A.M. Kaufman. Phys. Rev. X **8**, 041054 (2018).
[4] S. Saskin, …, J.D. Thompson. Phys. Rev. Lett.**122**, 143002 (2019).
[5] M. Norcia and F. Ferlaino, Nature Physics **17**, 1349-1357 (2021).
[6] D. Bloch, …, I. Ferrier-Barbut. Phys. Rev. Lett. **131**, 203401 (2023).
[7] D.S. Grün, S.J.M. White, …, F. Ferlaino. Phys. Rev. Lett. **133**, 223402 (2024)
[8] D.S. Grün, L.B. Giacomelli, …, F. Ferlaino. arXiv:2506.05123 (2025).

Cavity array microscopes for quantum science

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The combination of neutral atom arrays and optical cavity QED systems holds promise for realizing fast and non-destructive atom measurement, building large-scale quantum networks, and engineering hybrid atom-photon Hamiltonians. However, to date, experiments integrating the two platforms have been limited to interfacing the entire atom array with a global cavity mode, constraining parallelism and scalability.

We introduce the cavity array microscope [1], an experimental platform where each individual atom is strongly coupled to its own individual cavity across a two-dimensional array of over 40 modes. Our approach uses a new free-space cavity geometry with intra-cavity lenses to realize above-unity peak cooperativity with micron-scale mode waists and spacings, compatible with typical atom array geometries while keeping atoms far from dielectric surfaces. We show fast, non-destructive, parallel readout on millisecond timescales, including via a fiber array as a proof-of-principle for future networking. The platform is species-agnostic and scalable, and key metrics will further improve in an upcoming realization anticipated to be compatible with glass-cell-based experiments. Our work unlocks, for the first time, the regime of many-cavity QED, and opens an unexplored frontier of large-scale quantum networking with atom arrays.

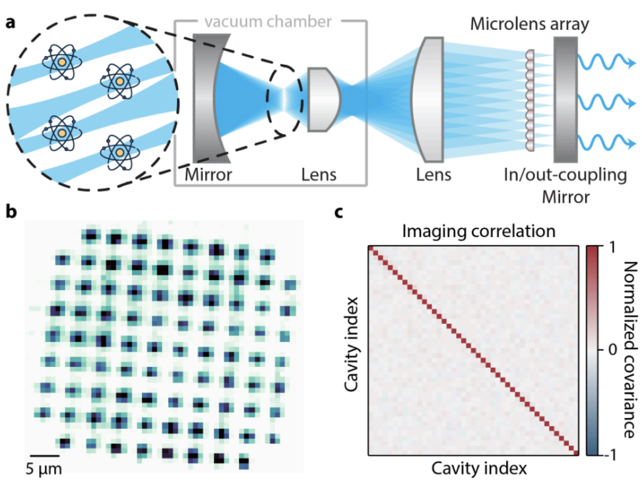

Fig 1. **The cavity array microscope.** a) Experimental geometry, showing intracavity lenses stabilizing the two-dimensional array of single-atom cavity modes. b) Average atomic fluorescence image, readout from the cavity, of dozens of modes each with a single atom, c) Cross-cavity correlations are <1%, indicating all modes are independent as desired.

References

[1] **A.L. Shaw***, A. Soper*, D. Shadmany*, A. Kumar, L. Palm, D. Koh, V. Kaxiros, L. Taneja, M. Jaffe, D. Schuster, J. Simon, arXiv:2506.10919 (2025)

Scalable Microlens-Based Integration of Rydberg-Interacting Quantum Arrays

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As inherently non-interacting particles with identical intrinsic properties, neutral atoms in tweezer arrays offer a versatile platform for quantum technologies. We present the realization of a large-scale quantum array architecture based on micro-fabricated lens arrays, surpassing the tier of 1000 atomic qubits. By combining two separate tweezer arrays in this manner, we achieve two-dimensional configurations comprising 3000 trap sites, providing an average of 1167 single atom qubits [1]. In addition, by "supercharging" one array designated as the quantum-processing unit (QPU) with atoms from the secondary array, we significantly increase the initial filling fraction. This advancement enables defect-free assembly of clusters containing up to 441 qubits (see Fig. 1). Due to the Talbot effect, the microlens-generated tweezer array extends to the third dimension at no additional cost. With tens of additional Talbot planes, we can access more than 10000 sites in the current setup [2].

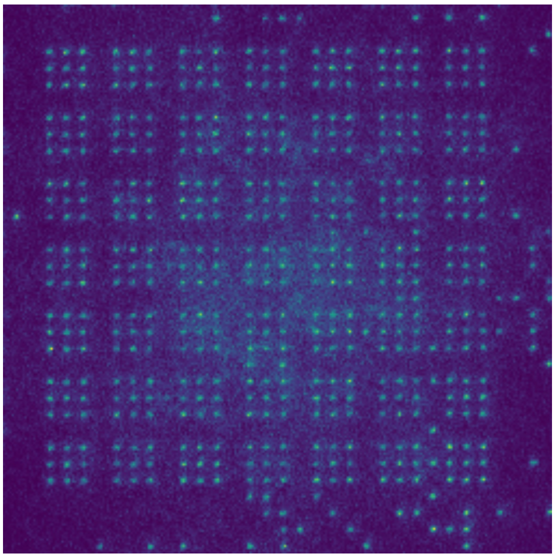

Fig. 1: Defect-free configuration of 49 clusters of 3x3 atoms, resulting in 441 qubits [1].

Local control of quantum states and interactions is achieved through fast laser addressing, enabling parallelized universal quantum operations including site-selective Raman and Rydberg excitation of atomic qubits [3].

A modular scheme with additional reservoir and buffer sites decouples the accumulation of cold atoms from the QPU operation [4]. In this fashion, configurations that mitigate immanent atom loss and address continuous operation have been realized. These advances facilitate the continuous operation of highly scalable quantum registers. They find immediate application in Rydberg-mediated quantum simulation, computation, metrology, and sensing, as demonstrated by the application of a tweezer array as a two-dimensional quantum sensor for magnetic fields consisting of 270 single-atom sensor pixels operated in parallel [5].

References

[1] L. Pause et al., Optica **11**, 222 (2024)

[2] M. Schlosser et al., Phys. Rev. Lett. **130**, 180601 (2023)

[3] M. Schlosser et al., J. Phys. B: At. Mol. Opt. Phys. **53**, 144001 (2020)

[4] L. Pause et al., Phys. Rev. Research **5**, L032009 (2023)

[5] D. Schäffner et al., PRX Quantum **5**, 010311 (2024)

Loading molecules... [█ █ █ █ ▯ 80%]

Scheme for Deterministic Loading of Laser-Cooled Molecules into Optical Tweezers

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Ultracold molecules, like CaF, provide a powerful platform for quantum computing. These molecules are arranged in a grid and are trapped by an optical tweezer array. To build this up, tweezers are loaded stochastically with 50% probability, which must be followed by rearrangement of these tweezers to create defect-free arrays. However, this can take too long compared to the lifetime of the molecules, which limits the scalability of such molecular quantum computers. Deterministic loading of tweezers with single molecules at 100% success rate is therefore desirable.

We propose a novel scheme to increase the efficiency [1]: repeatedly load laser-cooled molecules into optical tweezers, and transfer them to storage states that are rotationally excited by two additional quanta. Molecules in such states experience newly discovered rotational Van der Waals interactions with the ones that are loaded. We show using quantum scattering calculations that collisional loss of molecules in these storage states is suppressed [2], and a dipolar blockade prevents the accumulation of more than one molecule. This scheme greatly improves the efficiency to 80%, leading to the possibility of creating larger molecular quantum computers.

References

[1] E.F. Walraven, M.R. Tarbutt, and T. Karman, Phys. Rev. Lett. 132, 183401 (2024)
[2] E.F. Walraven and T. Karman, Phys. Rev. A 109, 043310 (2024)

Rydberg Macrodimers: From Polariton Decay to Molecular Interactions

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Rydberg macrodimers are molecules of two Rydberg atoms measuring up a micron in diameter [1]. Bound to by polarization forces, the bond energy energy can be as low as a few MHz, opening up new perspectives for light-mediated control of molecular bonds.

Here, I will revisit the familiar concept that coupling of an isolated quantum state to a continuum is associated with decoherence and decreased lifetime [3]. Due to their special properties [2], Rydberg macrodimers can overcome this dissipative mechanism and instead form bound states with the continuum of free motional states. This is enabled by the unique combination of extraordinarily slow vibrational motion in the molecular state and the optical coupling to a non-interacting continuum. Under conditions of strong coupling, we observe the emergence of distinct resonances where the macrodimer is hybridized with the continuum. For atoms arranged on a lattice, we predict molecules consisting of more than two atoms that appear in atom loss correlations in a quantum gas microscope. Our results present an intriguing light-mediated mechanism to control decoherence and bind multiatomic molecules using macrodimers. Finally, I will give an overview of ongoing work to compute the interactions between pairs of molecules, setting the stage for the investigation of many-body dynamics of Rydberg macrodimers.

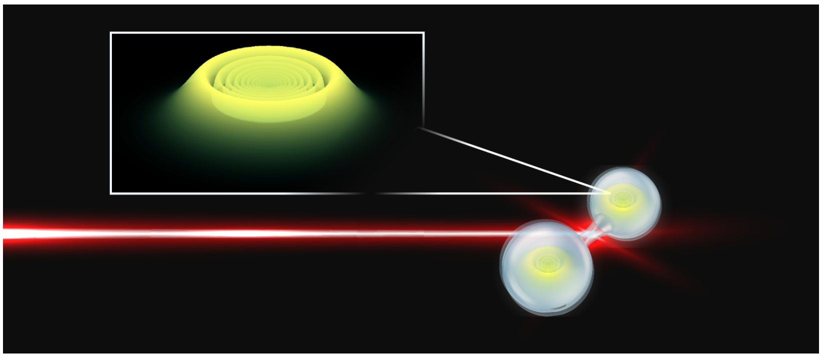

Figure 1: A macrodimer molecule is exposed to a strong dissociating laser field, and yet does not fall apart.

References

[1] S. Hollerith, J. Zeiher, J. Rui, A. Rubio-Abadal, V. Walther, T. Pohl, D. M. Stamper-Kurn, I. Bloch, & C. Gross, *Science*, **364**, 664 (2019)

[2] S. Hollerith, K. Srakaew, D. Wei, A. Rubio-Abadal, D. Adler, P. Weckesser, A. Kruckenhauser, V. Walther, R. van Bijnen, J. Rui, C. Gross, I. Bloch, & J. Zeiher, *Phys. Rev. Lett.*, **128**, 113602 (2022)

[3] S. Hollerith, V. Walther, K. Srakaew, D. Wei, D. Adler, D. Agrawal, P. Weckesser, I. Bloch, & J. Zeiher, *PRX Quantum*, **5**, 030335 (2024)

New opportunities in quantum simulation with ultrapolar molecules

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I will present new efforts at UChicago toward building novel quantum phases of matter using the emerging technology of highly polar molecules cooled to nanokelvin temperatures. Specifically, we hope to realize exotic topological superfluids built from interacting gases of KAg molecules, which could feature extraordinary characteristics such as resistance to disorder, frictionless flow, and the emergence of Majorana particles. Another complementary goal is to leverage the strong dipole-dipole interactions to pioneer novel ways to load molecules into defect-free, low-entropy arrays for realizations of lattice spin models.
We acknowledge funding from the Packard Foundation Fellowship.

Abstracts of Posters

(in alphabetical order)

Two-photon cooling of calcium atoms

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Our experiment aims to trap individual calcium atoms excited to circular Rydberg states and perform Quantum Non-Demolition (QND) readout of the qubit state, as proposed in Refs. [1, 2]. To achieve this, the first step is to cool and trap calcium atoms in optical tweezers.

Efficient cooling of neutral alkaline-earth atoms typically requires two Magneto-Optical Traps (MOTs). The initial broadband MOT is followed by a second MOT operating on a narrower transition. However, for certain atoms, such as magnesium and calcium, this transition is impractically narrow, necessitating additional quenching. To overcome this challenge, the initial cooling transition can be dressed with a high-intensity control beam, thereby altering the absorption spectrum of the initial cooling light [3, 4].

In our experiment, we implement this two-photon cooling technique on calcium atoms. The atoms are initially cooled in a MOT operating on the 423-nm 1S0 -> 1P1 transition. We subsequently switch on a single 1034-nm control beam, tuned to the 1P1 -> 4a5s 1S0 transition. This cooling forms a closed cycle, limiting losses due to decay channels, and could lead to temperatures as low as 150 μK. We will also present preliminary results on trapping calcium atoms in an optical tweezer.

References:

[1] C. Fischer, Quantum non-demolition readout for optically trapped alkaline-earth Rydberg atoms, PhD Thesis, ETH Zürich (2022)
[2] A. Muni et al., Optical coherent manipulation of alkaline-earth circular Rydberg states, Nat.Phys.18,502 (2022)
[3] T. Mehstaubler et al., Observation of sub-Doppler temperatures in bosonic magnesium, PhysRev. A 77, (2008)
[4] W. Magno et al., Two-photon Doppler cooling of alkaline-earth-metal and ytterbium atoms, PhysRev. A 67, (2003)

Few-body Förster resonances in Rydberg atoms for quantum gate protocols

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Neutral atoms arranged in reconfigurable arrays of optical tweezers present a promising platform for scalable quantum computing. However, despite notable progress, the realization of long-range multi-qubit gates remains a key challenge for this approach. Limited connectivity, due to the short-range nature of commonly used van der Waals interactions, constrains the complexity of quantum circuits feasible on current NISQ devices.

A promising strategy to overcome this limitation involves Stark-induced Förster resonances [1, 2]. By applying an external electric field, the Förster energy defect between collective Rydberg states can be tuned, leading to a resonant enhancement of dipolar interactions in the array. This enables coherent gate operations between qubits separated by tens of micrometers, significantly extending spatial connectivity.

We present recent theoretical results on Stark-tuned Förster resonance transfers in ordered arrays of Rb atoms. In this study, we have designed several high-fidelity (up to 99.7%) protocols for three-qubit Toffoli and CCPHASE gates [1, 3, 4]. We have also proposed techniques to improve robustness against experimental imperfections, including the use of spatially stable resonances and DC-inaccessible two-body transitions.

References

[1] I. I. Beterov, et al., Phys. Rev. A **98**, 042704 (2018).

[2] P. Cheinet, et al., Quantum Electronics **50**, 213 (2020).

[3] I. N. Ashkarin, et al., Phys. Rev. A **106**, 032601 (2022).

[4] I. N. Ashkarin, et al., Phys. Rev. Research **7**, 013034 (2025).

Arrays of long-lived circular Rydberg states of strontium

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Arrays of circular Rydberg atoms offer a unique opportunity to explore long-timescale quantum dynamics thanks to their millisecond-scale lifetimes in cryogenic environments, exceeding the limits of laser-accessible Rydberg states. However, trapping these states remains a challenge due to the repulsive ponderomotive potential experienced by their nearly free electron. While blue-detuned traps offer a solution, they require high laser power and limit scalability. An alternative approach is to use alkaline-earth-like atoms, where the polarizability of the ionic core allows optical trapping of circular Rydberg states. We have developed a cryogenic (4 K) experimental setup capable of trapping strontium atoms in optical tweezer arrays and exciting them to circular states. Ultimately, this configuration could allow direct imaging of trapped Rydberg atoms via a broad transition of the ionic core, bypassing the need to transfer the atoms back to the ground state. In addition, the electrostatic interaction between the Rydberg electron and the ionic core induces a Rydberg-state dependent shift in ionic transitions. This shift can be resolved spectroscopically, opening the way for non-destructive readout and coherent control of individual circular Rydberg atoms.

Rymax one: A neutral atom quantum processor to solve optimization problems

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Quantum computers are set to advance various domains of science and technology due to their ability to efficiently solve computationally hard problems. However, achieving such a quantum advantage is still hindered by the quality and scale of the available quantum computing hardware.

Here, we present the recent status of our project, Rymax One, which aims to build a quantum computer specifically designed to solve real-world optimization problems. To achieve this goal, we are using trapped arrays of ultracold Ytterbium atoms, whose level structure enables the realization of qubits with long coherence times, high-fidelity gate operations, and novel hardware-efficient encodings.

Measurement-free quantum error correction optimized for biased noise

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In this work, we derive optimized measurement-free protocols for quantum error correction and the implementation of a universal gate set optimized for an error model that is noise biased. The noise bias is adapted for neutral atom platforms, where two- and multi-qubit gates are realized with Rydberg interactions and are thus expected to be the dominating source of noise. Careful design of the gates allows to further reduce the noise model to Pauli-Z errors. In addition, the presented circuits are robust to arbitrary single-qubit gate errors, and we demonstrate that the break-even point can be significantly improved compared to fully fault-tolerant measurement-free schemes. The obtained logical qubits with their suppressed error rates on logical gate operations can then be used as building blocks in a first step of error correction in order to push the effective error rates below the threshold of a fully fault-tolerant and scalable quantum error correction scheme.

Interfacing a Rydberg Atom Array with an Optical Cavity

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We present progress on interfacing a Rydberg atom array with a high-finesse optical cavity. Atom arrays have emerged as a leading platform for quantum computation and simulation. Coupling an atom array to an optical cavity adds further capabilities to the neutral atom toolbox such as cavity-enhanced atom readout, tunable nonlocal interactions between atoms, and atom-photon entanglement. We use such capabilities to quickly and repeatedly readout arbitrary subsets of our atom array via the cavity. As a preview of intracavity qubit-qubit interactions mediated by Rydberg states, we couple an atomic ensemble to a Rydberg state and observe cavity EIT, recovering transmission of an otherwise blocked probe beam through the cavity. By leveraging the capabilities of an optical cavity and a Rydberg atom array, our system opens the door to fast, adaptive control methods and lays groundwork for measurement-based quantum computation and quantum simulation protocols.

References

[1] Beili Hu, Phys. Rev. Lett. 134, 120801 (2025)

Fast neutral atom transport and transfer between optical tweezers

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We study the optimization of neutral atom transport and transfer between optical tweezers, both critical steps in the implementation of quantum computers and simulators [2,5,6]. We analyze four experimentally relevant pulse shapes (piece-wise linear, piece-wise quadratic, minimum jerk, and a combination of linear and minimum jerk) and we also develop a protocol using Shortcuts-to-Adiabaticity (STA) methods to crucially incorporate the time-dependent effects of static traps [1,3,4]. By computing a measure of the final transport error and two measures of the heating during transport, we show that our proposed STA protocol comprehensively outperforms all the experimentally inspired pulses. After further optimizing the pulse shapes, we find a lower bound on the protocol duration, compatible with the time at which the vibrational excitations exceed half of the states hosted by the moving tweezer. This lower bound is at least eight times faster than the one reported in recent experiments, which highlights the importance of including and optimizing the transfer from and to static traps, that may be the largest bottleneck to speed. Finally, our STA results prove that a modulation in the depth of the moving tweezer designed to time-dependently counteract the effect of the static traps is key to reduce errors and pulse duration. To motivate the implementation of our STA pulses in future experiments, we provide a simple analytical approximation for the moving tweezer position and depth controls.

References

[1] E. Torrontegui, S. Ibáñez, X. Chen, A. Ruschhaupt, D. Guéry-Odelin, and J. G. Muga, Phys. Rev. A 83, 013415 (2011)
[2] M. R. Lam, N. Peter, T. Groh, W. Alt, C. Robens, D. Meschede, A. Negretti, S. Montangero, T. Calarco, and A. Alberti, Phys. Rev. X 11, 011035 (2021).
[3] Q. Zhang, J. G. Muga, D. Guéry-Odelin, and X. Chen, J. Phys. B: At. Mol. Opt. Phys. 49, 125503 (2016).
[4] X. Chen, E. Torrontegui, D. Stefanatos, J.-S. Li, and J. G. Muga, Phys. Rev. A 84, 043415 (2011).
[5] N. Rach, M. M. Müller, T. Calarco, and S. Montangero, Phys. Rev. A 92, 062343 (2015).
[6] T. Caneva, T. Calarco, and S. Montangero, Phys. Rev. A 84, 022326 (2011).

Critical velocity in superfluid states of hardcore Bose-Hubbard model with long-range hopping

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Long-range interacting spin systems, such as Rydberg atom arrays, dipolar Bose gases, and trapped ions, have attracted significant attention as a new platform for studying quantum many-body physics [1-5]. In particular, the spin-1/2 XY model with long-range interactions, which is realizable in Rydberg arrays [4] and trapped ions [5,6], can be effectively mapped onto a hard-core Bose-Hubbard model (HCBHM) with long-range hopping. Given that there is a superfluid state in the quantum phase diagram of the HCBHM with short-range interaction, it is interesting to study how the long-range nature of the hopping affects superfluidity. In this study, we analyze the superfluid critical velocity by applying a mean-field theory [3] to the HCBHM with long-range hopping that decays algebraically as ~ $1/r^b$. We find that when the power of the algebraic decay b decrease, the critical velocity vanishes at b=3, which corresponds to the case of the XY model realized with Rydberg atom arrays. In contrast, when b increases toward the nearest-neighbor limit, the critical velocity converges to a finite value consistent with known results of the short-range interaction [3].

References

[1] D. Peter, et al, Phys. Rev. Lett. 109, 025303 (2012)
[2] O. K. Diessel, et al, Phys. Rev. Research 5, 033038 (2023)
[3] I. Danshita and D. Yamamoto, Phys. Rev. A 82, 013645 (2010)
[4] C. Chen, et al, Nature 616, 691-695 (2023)
[5] R. Richerme et al., Nature 511, 198 (2014).
[6] N. Kotibhaskar, et al, Phys. Rev. Research 6, 033038 (2024)

Quantum Wires and Local Light Shifts for Graph Optimisation on Rydberg Atom Arrays

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Combinatorial optimisation problems are central to many scientific and industrial applications but their NP-hardness often hinders the development of efficient algorithms to solve them [1]. Quantum optimisation offers a promising path forward, with neutral atom quantum computers emerging as a prominent platform due to their scalability, high connectivity, and ability to implement programmable spin systems with tunable interactions [2]. In such platforms, the Rydberg blockade enables direct mapping of maximum independent set (MIS) problems onto unit-disk graphs (UDGs), with quantum annealing being used to access solutions encoded in many-body ground-states [3].

Building on this approach, we experimentally demonstrate the implementation of vertex weighting via local control fields to embed maximum weighted independent set (MWIS) problems on UDGs [4]. This mapping also supports broader problem classes such as non-UDG MWIS and quadratic unconstrained binary optimisation (QUBO), though embedding overhead remains a challenge for state-of-the-art platforms [5]. For quasi-UDGs, we overcome this issue using a hardware-efficient mapping with quantum wires—chains of atoms that connect distant vertices—reducing ancillary qubit requirements [6]. Our experimental results show successful preparation of MWIS and QUBO solutions on graphs of up to 28 atoms, demonstrating the viability of our method for small-scale quantum optimisation on near-term hardware.

References

[1] V. T. Paschos, *Applications of combinatorial optimization*, Vol. 3 (John Wiley & Sons, 2014).

[2] L. Henriet *et al.*, *Quantum computing with neutral atoms,* Quantum **4**, 327 (2020).

[3] S. Ebadi *et al.*, *Quantum optimization of maximum independent set using Rydberg atom arrays* Science **376**, 1209 (2022).

[4] A. G. de Oliveira *et al.*, *Demonstration of Weighted-Graph Optimization on a Rydberg-Atom Array Using Local Light Shifts,* PRX Quantum **6**, 010301 (2025).

[5] L. Bombieri *et al.*, *Quantum adiabatic optimization with Rydberg arrays: localization phenomena and encoding strategies,* PRX Quantum **6**, 020306 (2025)

[6] J. Kombe *et al.*, *A quantum wire approach to weighted combinatorial graph optimisation problems,* arXiv:2503.17115 (2025).

Triplon dynamics in Floquet-driven Rydberg quantum simulators

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We analyze how Floquet engineering enables the emergence and manipulation of three-spin bound states (triplons) in one- and two-dimensional systems of Rydberg atoms based on recent driving protocols (WAHUHA). We derive the effective Hamiltonian up to second order in the driving frequency and identify regimes where an approximate SO(2) symmetry ensures quasi-conservation of magnetization. We study the propagation of triplons in systems of various sizes and interaction ranges, highlighting how correlated hopping and long-range couplings significantly enhance their mobility. The resulting dynamics agrees well with exact simulations for moderate driving frequencies, suggesting feasible experimental implementation. Finally, we discuss how higher-dimensional geometries and dipolar interactions can stabilize bound-state transport against symmetry-breaking effects. Our findings provide a blueprint for observing Floquet-induced quasiparticles in programmable quantum simulators, with implications for non-equilibrium many-body physics and exotic excitation transport.

Anisotropic and Non-Additive Interactions of a Rydberg Impurity in a BEC

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Quantum impurity problems have long relied on the simplifying assumptions of spherically symmetric, additive interaction potentials—yet real-world interactions are often inherently anisotropic and non-additive. Here, a Rydberg impurity immersed in a Bose–Einstein condensate presents an ideal, tunable, and experimentally accessible platform to explore these complexities. The Rydberg atom's electronic wave function extends so far that its interaction range can rival—or even exceed—the condensate's mean interparticle spacing. By selecting the principal quantum number and exciting to *l>0* states, one breaks spherical symmetry and accesses degenerate m-levels whose mixing generates genuine non-additive forces. We calculate the full many-body absorption spectrum of such a Rydberg impurity in an ideal BEC, identifying signatures of attractive and repulsive polarons, bound molecular states, and a crossover to classical, mean-field behavior. We further show how two-body partial-wave scattering is shaped by Feshbach-type resonances and how anisotropic interactions leave distinct fingerprints in the spectrum.

References

[1] A. A.T. Durst, M. T. Eiles, PRR **6**, L042009 (2024)

Optimal control in phase space applied to minimal-time transfer of thermal atoms in optical traps

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We present an optimal control procedure for the non-adiabatic transport of ultracold neutral thermal atoms in optical tweezers [1], with focus on reaching minimal transfer time. The particle dynamics are modeled first using a classical approach through the Liouville equation and second through the quantum Wigner equation to include quantum effects. Both methods account for typical experimental noise described as stochastic effects through Fokker-Planck terms, such as laser phase noise, finite atom temperature, beam-pointing and depth fluctuations of the tweezer trap. The optimal control process is initialized with a trajectory computed for a single classical particle and determines the phase-space path that minimizes transport time and ensures high transport fidelity to the target trap.

We study the optimal control procedure to steer a ^{88}Sr atom from an 0.1 mK deep initial trap to a target site 10 μm away. We identify an absolute minimum with flying time of 7.36 μs and a high fidelity of 99.97% in the classical case. For the quantum case with a ^{6}Li atom, leveraging the same trajectory and flying time, we reach a fidelity of 98.95%. We test the robustness of the optimal control procedure and analyze the heating of the atom that occurs during the transport, identifying avenues to achieve a favorable trade-off between the transfer speed and the energy increase.

Moreover, we are currently testing these predictions on a novel apparatus with ^{88}Sr atoms trapped in reconfigurable optical tweezers [2] using AODs and a kHz rate SLM, benchmarking sequential and parallel approaches. This technique provides the fastest and most efficient method for relocating atoms from an initial configuration to a desired target arrangement, minimizing time and energy costs while ensuring high fidelity. Such an approach may be highly valuable to initialize large atom arrays for quantum simulation or computation experiments.

References

[1] O. Morandi, S. Nicoletti, V. Gavryusev, L. Fallani, arXiv:2501.10494

[2] V. Gavryusev et al., Quantum 2.0 Conference and Exhibition, Technical Digest Series (Optica Publishing Group, 2024), paper QTh2A.2.

New generation Rydberg atom array quantum simulator

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In the context of quantum simulation of many-body spin Hamiltonians, in our first generation experiment, we implemented the *XY* spin model [1,2] with Rydberg states. We recently implemented the *t-J* spin model [3], encoding the atoms on three Rydberg states and using dipolar and van der Waals interactions. In particular, this makes it possible to study unreachable parameter ranges in optical lattices or condensed matter physics, where this model is generally studied.

I will then present an update on the construction of a new generation of our Rydberg atom array quantum simulator. The construction of this new experiment targets the improvement of several important features of the machine. For example, using a high NA and large field-of-view microscope objectives allows for the manipulation of larger matrices (about 400 atoms routinely). We will also implement new experimental developments such as quasi-continuous reloading of tweezer arrays and fast, lossless detection. These improvements will increase the programmability of the platform and to enlarge the class of Hamiltonian we can study, reaching a regime of large quantum states very challenging to simulate on classical computer.

References

[1] C. Chen *et al.*, "Spectroscopy of elementary excitations from quench dynamics in a dipolar XY Rydberg simulator", ArXiv 2311.11726, (2023), to appear in Science.

[2] G. Emperauger *et al.*, "Tomonaga-Luttinger Liquid Behavior in a Rydberg-encoded Spin Chain", ArXiv 2501.08179, (2025), to appear in PRX.

[3] M. Qiao *et al.*, "Realization of a doped quantum antiferromagnet with dipolar tunnelings in a Rydberg tweezer array", ArXiv 2501.08233, (2025), to appear in Nature.

Towards Quantum Simulation with Cesium Atomic Ensembles in Optical Tweezers

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We are upgrading our cold atom setup for quantum simulation with cesium atomic ensembles with Rydberg excitations detected via electromagnetically induced transparency, inspired by Ref. 1. For this, we designed and built a pair of identical homemade optical objectives to use for imaging and creation of optical tweezer traps in the experiment. We present the design and the initial testing of the objectives. Before the upgrade, we tested the use of AOD-based time-multiplexed optical tweezers for the preparation of atomic-ensemble arrays [2]. We present the progress of the upgrade, including Rydberg state spectroscopy with room-temperature cesium, as well as laser cooling and trapping atoms in optical tweezers.

References

[1] W. Xu *et al*., Phys. Rev. Lett. **127**, 05501 (2021).

[2] K. Gosar *et al.*, Phys. Rev. A **106**, 022604 (2022).

Toward the simulation of the Jaynes-Cummings Hamiltonian in blockaded arrays of ultracold atoms

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Strong Rydberg interactions, arising from the large dipole moments of Rydberg states, have been extensively studied in recent years for both digital and analog quantum computing applications. By positioning individual Rydberg atoms within a common Rydberg blockade radius, it is possible to emulate the strong light-matter interactions of cavity QED systems and implement the Jaynes-Cummings (JC) Hamiltonian without the need of a cavity [1]. The possibility to address the entire dressed state basis could allow for the encoding of qudits for quantum computing applications [2]. To implement this Hamiltonian experimentally, we excite atoms in Rydberg states using a two-photon transition. The normal excitation scheme combines two transitions in the visible spectrum. However, the low dipole matrix element of the intermediate state to Rydberg transitions at 460 nm and the limited commercially available blue laser power limit the coupling strength to Rydberg states. To circumvent this limitation, I have designed and constructed a new laser system to implement the inverted excitation scheme. In this approach, the intermediate state is coupled to the ground state via a transition at 405 nm, while the Rydberg transition is addressed by a high-power 10 W laser at 976 nm [3] allowing for larger Rabi coupling. This excitation scheme additionally takes advantage of the longer lifetime of the first excited state. Therefore, we expect an enhancement of the Rabi oscillation coherence time of more than one order of magnitude [4]. I will report on our most recent results using the normal scheme, present the design and characterization of this new laser system, and outline our preliminary results toward the realization of JC Hamiltonian in blockaded arrays of ultracold Rydberg Potassium atoms.

References

[1] J. Lee, et. al., Phys. Rev. A 95 (2017)
[2] A. Robert et. al., arXiv:2502.06465 (2025)
[3] T.-L. Chen, et. al., Phys. Rev A 101 (2020)
[4] P. Scholl, Ph.D. thesis (2022)

Mimicking emergent geometry with real geometry in Rydberg atoms

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We consider sparse models that connect spins separated by distances that are integer powers of 2, proposed by [1], based on an experimental scheme laid out in [2], and that relate neatly to 2-adic numbers [3]. These sparse models have been receiving increasing attention as they have been shown to exhibit fast scrambling and can prepare highly entangled states as a resource for quantum metrology [4,5]. Their rich behaviour arises from the coupling parameter, which allows continuous tuning of the underlying geometry of the interaction graph. Here, we expand on previous work and explore the influence of geometry in our model. We focus on whether the underlying geometrical transformations induce ground-state phase transitions. In particular, we ask whether classical geometrical phases persist in the presence of quantum fluctuations, allowing us to assess the robustness of distinct phases under experimentally relevant conditions. Crucially, we propose a realization of these models in Rydberg atom arrays by directly mapping the emergent interaction graph onto the physical layout of the atoms. In this way, the real-space geometry of the experimental platform can be used to mimic the emergent geometry of the model itself, providing a new route to engineer and explore complex quantum phases in long-range interacting systems.

References

[1] G. Bentsen, Y. Gu, and A. Lucas, Proceedings of the National Academy of Sciences 116, 6689–6694 (2019).

[2] C.-L. Hung, A. Gonzalez-Tudela, J. I. Cirac, and H. J. Kimble, Proceedings of the National Academy of Sciences 113, 10.1073/pnas.1603777113 (2016).

[3] S. S. Gubser, J. Knaute, S. Parikh, A. Samberg, and P. Witaszczyk, Communications in Mathematical Physics 352, 1019–1059 (2017).

[4] G. Bentsen, T. Hashizume, A. S. Buyskikh, E. J. Davis, A. J. Daley, S. S. Gubser, and M. Schleier-Smith, Phys. Rev. Lett. 123, 130601 (2019).

[5] S. Kuriyattil, P. M. Poggi, J. D. Pritchard, J. Kombe, and A. J. Daley, Phys. Rev. Lett. 134, 240801 (2025).

Sensing spatially varying electric fields through Rydberg atom networks

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In this work, we establish the foundation for a quantum sensor that detects a spatially varying electric field through Rydberg atom networks. A crucial aspect of our method is the phenomenon of Rydberg blockade, which arises from strong dipolar interactions and its dependence on the electric field surrounding the Förster resonance. We demonstrate how one can sense the latter by observing the variation in the size and frequency of the blockade across the network of Rydberg atoms. By tracking the dynamics of Rydberg excitations in systems of various sizes and employing the density-density correlator, we illustrate the collective effect of the blockade radius and elucidate different configurations of applied electric fields across the atom networks. Furthermore, through the use of Bayesian statistics, we determine specific values for the electric field near the Förster resonance.

Entangled states from sparsely coupled spins for metrology with neutral atoms

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Quantum states featuring extensive multipartite entanglement are a resource for quantum enhanced metrology, with sensitivity up to the Heisenberg limit. However, robust generation of these states using unitary dynamics typically requires all-to-all interactions among particles. Here, we demonstrate that optimal states for quantum sensing can be generated with sparse interaction graphs featuring only a logarithmic number of couplings per particle. We show that specific sparse graphs with long-range interactions can approximate the dynamics of all-to-all spin models, such as the one-axis twisting model, even for large system sizes. The resulting sparse coupling graphs and protocol can also be efficiently implemented using dynamic reconfiguration of atoms in optical tweezers.

References

[1] S. Kuriyattil *et al.*, `arXiv:2412.10010`

Vibrationally coupled Rydberg atom-ion molecules

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Recently, a new type of a long range molecule consisting of an ion and a Rydberg atom popularly known as Rydberg atom-ion molecules (RAIMs) has been theoretically proposed [1, 2] and experimentally observed in an ultracold cloud of $^{87}\mathrm{Rb}$ atoms [3]. We use a hybrid atom-ion system to create a linear crystal of ions in a Paul trap with RAIMs attached to its either end to generate ion-mediated Rydberg-Rydberg interactions. We propose a scheme to utilise the common motional modes of a crystal of trapped ions to enhance (facilitation) or suppress (blockade) the probability of forming two RAIMs at the ends of the chain, replacing the typical blockade radius set by the dipole-dipole interaction by the length of the ion crystal. We use detailed Floquet analysis to demonstrate the feasibility of our scheme in the presence of the time dependent rf potential of the Paul trap and identify parameter regimes where the RAIM survives, using an approach based on Landau-Zener-Stückleberg interferometry which studies the effect of an oscillating field on Landau-Zener (LZ) processes [4], aided by scaling arguments. Lastly, we outline future plans on how these RAIMs could potentially be detected in our hybrid atom-ion experiment [5] without the application of an ion microscope.

References

[1] M. Deiß et al., Atoms 9, 34 (2021).
[2] A. Duspayev et al., Phys. Rev. Research 3, 023114.
[3] N. Zuber et al., Nature 605, 453–456 (2022).
[4] S. Shevchenko, Physics Reports 492 , 1 (2010)
[5] H. Hirzler et al., Phys. Rev. A 102, 033109 (2020).

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Realization of a doped $t - J$ model in a Rydberg tweezer array

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Doping an antiferromagnetic Mott insulator is central to our understanding of a variety of phenomena in strongly-correlated electrons, including high-temperature superconductors. To describe the competition between tunneling t of hole dopants and antiferromagnetic spin interactions, theoretical and numerical studies often focus on the paradigmatic $t - J$ model, and the direct analog quantum simulation of this model in the relevant regime of high-particle density has long been sought. My group has realized a doped quantum antiferromagnet with next-nearest neighbour tunnelings t' and hard-core bosonic holes using a Rydberg tweezer platform [1]. We utilize coherent dynamics between three Rydberg levels, encoding spins and holes, to implement a tunable bosonic $t - J - V$ model (Fig.1) allowing us to study previously inaccessible parameter regimes [2]. We observe dynamical phase separation between hole and spin domains for $|t/J| \ll 1$, and demonstrate the formation of repulsively bound hole pairs in a variety of spin backgrounds. The interference between NNN tunnelings t' and perturbative pair tunneling gives rise to light and heavy pairs depending on the sign of t. Using the single-site control allows us to study the dynamics of a single hole in 2D square lattice (anti)ferromagnets. The model we have implemented extends the toolbox of Rydberg tweezer experiments beyond spin-1/2 models to a larger class of $t - J$ and spin-1 models.

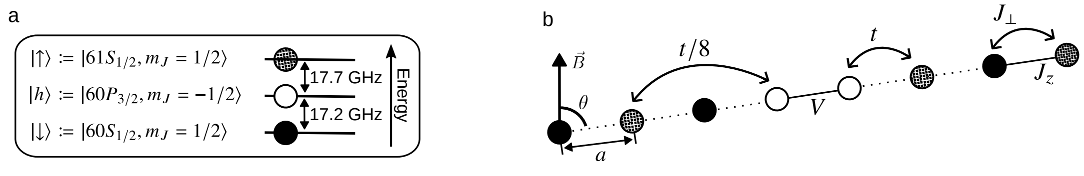

Figure 1: **Implementation of a $t - J - V$ model in a Rydberg tweezer array. a,** Encoding of the spin states in three Rydberg levels. **b,** Representation of the different interactions.

References

[1] M. Qiao *et al.*, arXiv:2501.08233

[2] L. Homeier *et al.*, Phys. Rev. Lett. **132**, 230401 (2024)

Methods and systems for imaging magnetic fields using Rydberg atom arrays

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Quantum processors have the potential to deliver a quantum advantage in various practical applications. Among the various platforms under development, Rydberg atom arrays stand out for their scalability, controllability, and versatility. A critical challenge is scaling up these processors without compromising on their control performance. An ongoing problem is creating large configuration of atoms whose properties are uniform in space and stable in time. In this poster, I describe new methods and systems to improve the spatio-temporal homogeneity of arrays of optical traps and discuss how they can help achieve greater performance in microwave-pulse experiments for imaging magnetic fields.

First, I will present a method for correcting astigmatism and ellipticity in Gaussian beams [1]. Then, I will describe a feedback control system for uniformizing and stabilizing the trap depth of more than a thousand traps in real time, allowing for a reduction in shot-to-shot fluctuations in loading efficiency and an increase in relative stability when performing adiabatic ramp-down experiments. Next, I will present the details of a low-latency reconfiguration system for solving atom reconfiguration problems, as needed for generating large, defect-free configurations of atoms with high success rate [2-5]. Finally, I will show how these systems and methods can be used to improve microwave-pulse experiments towards spatio-temporal imaging of magnetic fields.

By measuring magnetic fields on microsecond and micrometer scales, these methods enable new experiments in noise spectroscopy and local magnetic field sensing. These findings not only improve the controllability of the Rydberg Atom Array platform by correcting for deleterious noise sources, but also enable in-situ characterization of fluctuating magnetic fields.

References

[1] S. Khoubyarian, preprint (2025).
[2] A. Dadpour, arXiv **2504.06528** (2025)
[3] F. Afiouni, arXiv **2504.06182** (2025)
[4] R. El Sabeh, Phys. Rev. A **108**, 023108 (2023)
[5] B. Cimring, Phys. Rev. A **108**, 023107 (2023)

Insights into quantum “radiation” metrology

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We investigate **radiation metrology**—the problem of inferring the dynamics of a Markovian open quantum system by continuously monitoring the radiation it emits into its environment [1]. Unlike conventional quantum metrology, which typically relies on repeated state preparation, radiation metrology offers a route to achieving Heisenberg-limited precision without such repetition. Leveraging connections with matrix product state techniques, we derive compact analytical expressions for the ultimate precision bounds, as measured by the quantum Fisher information [2]. We analyze how this precision scales with time and particle number, particularly in the vicinity of dissipative phase transitions [3]. Additionally, we propose protocols for engineering optimal open quantum sensors and discuss the practical challenges of accessing the full quantum Fisher information in experimental settings.

References

[1] Gammelmark, Søren, and Klaus Mølmer. "Bayesian parameter inference from continuously monitored quantum systems." *Physical Review A—Atomic, Molecular, and Optical Physics* 87.3 (2013): 032115.
[2] Midha, Siddhant, and Sarang Gopalakrishnan. "Metrology of open quantum systems from emitted radiation." arXiv preprint arXiv:2504.13815 (2025).
[3] Ilias, Theodoros, et al. "Criticality-enhanced quantum sensing via continuous measurement." *PRX Quantum* 3.1 (2022): 010354.

Quantum Technology Platform Beyond 1000 Atomic Qubits for Quantum Simulation, Computation, Metrology, and Sensing

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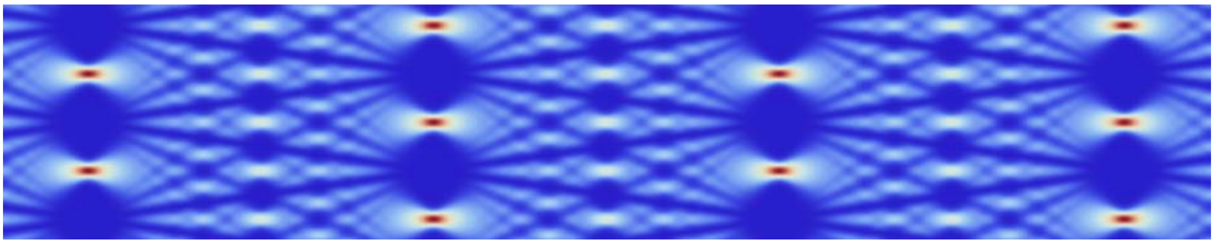

Quantum arrays of neutral atoms in regular optical potentials of multi-site tweezer networks and optical lattices foster numerous applications in quantum optics, metrology, and information science, where comprehensive laser control enables the realization of textbook examples of quantum models. We create microlens-based tweezer arrays that pave the way to a scalable platform for Rydberg-mediated quantum physics [1, 2].

Specific to our approach, microlens arrays not only create a single focal plane but also give multiple Talbot layers suitable for trapping and manipulating indiviual atoms. Thus, they allow scaling the number of available qubits without requiring additional laser power. Multiple Talbot layers can be addressed, scaling the system size to 10,000 usable sites [3].

Beyond the main targeted application in quantum simulation and computation, for the first time, a practical use case of tweezer arrays in quantum sensing has been demonstrated by utilizing an assembled 2D array of atoms as a magnetic field detector with parallelized operation of 270 single-atom sensor pixels with 7 micrometer spacing and sub-micrometer spatial resolution [4].

For future advancements of this platform, scaled and parallelized control techniques are key. A main limitation is given by the transport of atoms within a tweezer array. Optical tweezers generated by two crossed AODs have become the standard method to generate movable tweezers with their position depending on the radio frequency supplied. To overcome the limitation of single tweezers, it is possible to provide a multi-tone signal, generating multiple tweezers. Although conceptually simple, such an approach presents numerous challenges for the RF signal generation and for the control setup to coordinate multiple parallelized tweezers.

References

[1] L. Pause et al., Phys. Rev. Research **5**, L032009 (2023)
[2] L. Pause et al., Optica **11**, 222 (2024)
[3] M. Schlosser et al., Phys. Rev. Lett. **130**, 180601 (2023)
[4] D. Schäffner et al., PRX Quantum **5**, 010311 (2024)

PairInteraction v2: An Open-Source Toolkit for Fast and Accurate Calculations of Rydberg Interactions

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Rydberg atoms are utilized in a variety of experimental applications, including quantum simulations, ultracold chemistry, and quantum information. Their strong and highly tunable interactions – e.g. via external fields and their inter-atomic distance – make them a powerful platform for these applications. Many of these experiments are conducted with such high precision that perturbative calculations of the interaction potentials are insufficient, and exact calculations are needed. In this poster, we present a new version of the pairinteraction software, an open-source tool for calculating the interaction potentials between two Rydberg atoms in arbitrary fields, as well as useful properties like dipole matrix elements and effective Hamiltonians. The updated pairinteraction version now includes simulations of alkaline earth atoms, described by multichannel quantum defect theory (MQDT), leading to larger Hilbert spaces. These calculations are now feasible due to the improved performance of the C++ backend. Additionally, the new version features a Python package that abstracts the C++ backend, providing users with a high-level and easy-to-use Python interface.

Local Control in a Sr quantum computing demonstrator

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Digital quantum simulations and quantum error correction protocols require the application of local gates. We demonstrate such local control in a neutral atom array platform by locally shifting the qubit's frequency using off-resonant light. We show precise, highly parallel, local Z-rotations with low crosstalk. Together with global X-rotations, which have been optimized for minimizing motional entanglement using optimal control, this approach can be used to locally implement universal single-qubit operations. Together with two-qubit operations based on strong Rydberg blockade, we can realize a universal quantum gate set. Equipped with qubit shuttling, our new platform opens an exciting frontier for quantum computing, digital quantum simulation as well as quantum metrology.

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Rydberg-Cavity Platforms: Quantum Spin Liquids and Locality from All-To-All Interactions

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Neutral atoms individually trapped in arrays of optical tweezers and featuring strong, controllable Rydberg interactions have emerged as a leading platform for quantum information processing and the exploration of synthetic quantum matter. More recently, there have been efforts to integrate optical tweezer arrays with high-finesse optical cavities (see *Figure 1*). Beyond a quantum information processing advantage, the question of what novel paradigms might emerge for synthetic quantum matter (and/or light) has hardly been explored.

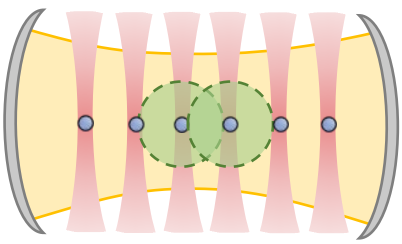

Figure 1 – Illustration of Rydberg atoms in an optical tweezer array inside of a cavity.

We propose that Rydberg tweezer-cavity systems can serve as a novel paradigm to study quantum spin liquids (QSLs) [1]. QSLs, which for example are predicted to emerge as the ground states of certain frustrated spin models, have a host of interesting properties. For example, two QSLs might be in distinct phases but still not break any symmetry (rotational, spatial) of the system. Because of the absence of magnetic order, their elementary spin excitations are no longer magnons, but fractionalized excitations that can have non-trivial (anyonic) particle statistics.

Here, these QSLs emerge in the presence of all-to-all interactions and thus, fall outside of the expected paradigm due to the absence of locality. While its groundstate and singlet excitations can be mapped to a known model, the nature of its spin excitations remains an open question. We also discuss how partial locality emerges.

Quantum Nucleation of Structured Clusters under Kinetic Constraints

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The growth of large structures from small seeds is a ubiquitous paradigm in physics, whether it is snowflakes nucleating from a dust particle or structure formation in the early universe seeded by quantum fluctuations. Here, we present experimental insights into the seeded emergence of structurally rich domains on a programmable 10×10 array of Rydberg atoms subject to kinetic constraints. By inducing excitations into an otherwise paramagnetic background, we trigger nucleation seeds. We observe the growth of domains governed by the interplay between facilitation and blockade mechanisms, study their structures, including branching and anisotropic growth, and compare them to the classical expectation. Our results reveal a new mechanism for domain formation in a deterministically prepared spin system and demonstrate how Rydberg quantum simulators are ideal for microscopic studies of quantum nucleation in one- and two-dimensional systems.

Fast number-resolved detection of ytterbium arrays

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In this contribution [1], I will report fast and low-loss single-atom imaging in optical tweezers without active cooling, enabled by the favorable properties of ytterbium. Collecting fluorescence over microsecond timescales, we reach single-atom discrimination fidelities above 99.9% and single-shot survival probabilities above 99.5%. Through interleaved recooling pulses, as short as a few hundred microseconds for atoms in magic traps, we perform tens of consecutive detections with constant atom-retention probability per image, an essential step toward fast atom re-use in tweezer-based processors and clocks. Our scheme does not induce parity projection in multiply-occupied traps, enabling number-resolved single-shot detection of several atoms per site. This allows us to study the near-deterministic preparation of single atoms in tweezers driven by blue-detuned light-assisted collisions: our experiments will provide a benchmark for future theoretical efforts aimed at finding optimal regimes for loading efficiency and speed. Moreover, the near-diffraction-limited spatial resolution of our low-loss imaging enables number-resolved microscopy in dense arrays, opening the way to direct site-occupancy readout in optical lattices for density fluctuation and correlation measurements in quantum simulators, without necessitating dynamical adjustment of atom-spacing. These results position fast in-trap imaging as a compelling approach for atom detection in quantum simulation, metrology and computing platforms.

References

[1] A. M. Falconi *et al*, arXiv preprint arXiv:2507.01011 (2025).

High-rate quantum LDPC codes for long-range-connected neutral atom registers

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High-rate quantum error correcting codes with moderate overheads in qubit number and control complexity are highly desirable for achieving fault-tolerant large-scale quantum computation. Recently, quantum error correction has experienced significant progress both in code development and experimental realizations, with the neutral atom qubit architecture rapidly establishing itself as a leading platform in the field. While codes with low qubit overhead and large error suppression do exist, they involve a degree of non-locality that has yet to be integrated into experimental platforms. In this work, we analyze a family of high-rate quantum Low-Density Parity-Check (LDPC) codes with limited long-range interactions and outline a near-term implementation in neutral atom registers. By means of circuit-level simulations under range-dependent depolarizing noise, we find that these codes outperform surface codes in all respects at experimentally achievable noise rates. By using multiple laser colors, we show how these codes can be natively integrated in two-dimensional static neutral atom qubit architectures with open boundaries, where the desired long-range connectivity can be targeted via the Rydberg blockade interaction. Finally, we show how circuit-level thresholds and logical error probabilities can be significantly improved by exploiting hardware-specific noise biases. We analyze the case where most errors are erasures, i.e. heralded qubit losses, which can be realized in Alkaline-earth(-like) atom qubits and compare the performance of our code family against bivariate bicycle quantum LDPC codes.

References

[1] L. Pecorari, et al. Nature Commun. **16**, 1111 (2025)
[2] L. Pecorari and G. Pupillo. arXiv:2502.20189 (2025)
[3] S. Bravyi, et al. Nature **627**, 778 (2024)

A new Strontium Rydberg tweezers experiment for the study of lattice gauge theories

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Lattice gauge theories are at the core of our current understanding of nature, from high energy physics to condensed matter systems. The numerical methods to compute lattice gauge theories have been extensively developed in the last decades. Nevertheless, they still suffer from limitations when computing dynamics or studying large system sizes. In this regard, quantum simulators offer a promising alternative to deal with lattice gauge theories [1]. While remarkable results have already been achieved for one dimensional systems, extensions to two dimensions remain a challenge.

In this work, we are developing a cold strontium-88 platform based on arrays of Rydberg atoms trapped in optical tweezers to perform simulations of lattice gauge theories. As a proof of principle, we intend to simulate the Rokhsar-Kivelson Hamiltonian using a dual Ising spin formulation [2]. The Rokhsar-Kivelson Hamiltonian features the so-called plaquette interactions akin to the magnetic interactions in electromagnetism. In this poster, I describe the design and the status on the construction and performance of the experimental apparatus. In particular, I detail the vacuum environment of the experiment, the progress towards the cooling strategy that will enable us to trap the atoms in optical tweezers, how we will excite them to Rydberg states and our system of coils and electrodes.

References

[1] M. C. Bañuls et al., EPJD **74**, 165 (2020).

[2] A Celi et al., PRX **10**, 021057 (2020).

Quantum Computation with Neutral Ytterbium Rydberg Atoms
in Optical Tweezer Arrays

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Arrays of neutral Rydberg atoms have evolved into a leading platform for quantum computation and simulation. Alkaline-earth-like atoms promise to overcome present limitations imposed on fault-tolerant quantum computation with its two-valence electron structure and single-photon Rydberg transitions, enabling novel qubit architectures, advanced error correction schemes and mid-circuit readout.
Here we present our experimental approach to building an ytterbium-based Rydberg tweezer experiment and report on the recent results on trapping and imaging fermionic ^{171}Yb atoms in triple magic optical tweezer arrays.
We introduce a machine learning assisted two-qubit gate design utilizing a hybrid-classical optimizer to construct fidelity-optimal pulse sequences for realizing CNOT gates, while assuming feasible experimental parameters. Furthermore, we show results on the successful suppression of servo noise by more than 20dB for our Rydberg laser system to significantly enhance excitation and gate fidelities. Finally, we report on the realization of a high switching speed, scalable single atom addressing system combining the benefits of a LCoS spatial light modulator and a digital mirror device capable of generating arbitrary patterns and enabling full aberration compensation.

Building a Programmable Quantum Gas Microscope

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Ultracold atoms in optical lattices offer a versatile platform for exploring strongly correlated quantum matter. While quantum gas microscopy techniques have enabled unprecedented single-site resolution, some of the remaining challenges of the field are still posed by rigid lattice configurations and slow cycle times.

In this contribution, we present our ongoing efforts in the building of a next-generation quantum gas microscope. Our experiment, designed to work with fermionic and bosonic lithium atoms, relies on atom-by-atom assembly in small lattice systems by means of auxiliary optical tweezers, combined with all-optical cooling techniques to facilitate sub-second experimental cycles.

Additionally, the holographic projection of a blue-detuned, short-spacing lattice will provide reconfigurability and fast dynamics, leading to diverse research avenues, from the simulation of phases of matter predicted by Hubbard models to topological phases and frustrated systems with unconventional lattice geometries.

Doppler heating in cold atoms

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Although laser cooling has been extensively studied and applied for decades, its heating counterpart has remained less explored. Nonetheless, laser heating can lead to interesting effects, such as mechanical instabilities in illuminated optical cavities [1] and the emergence of bimodal spatial profiles in molecules [2]. This research focuses on the Doppler heating mechanism in cold atoms, serving as a counterpart for the well-known Doppler cooling. We employ a Doppler velocimetry technique based on Rydberg spectroscopy. The key idea is that the Doppler shift in the absorption frequency of the Rydberg transition directly encodes the atomic velocity, allowing us to extract detailed velocity distributions with minimal perturbation to the system. Our Rydberg-based velocimetry offers several advantages over conventional methods: high spectral resolution with low signals, applicability across a wide range of cloud temperatures (limited only by the linewidths of the excitation lasers), locality of the measurements, and the ability to map both spatial profiles and momentum-position correlations through arrival-time analysis of the ions. Combining the results from this experimental technique and theoretical kinetic simulations, we reveal the appearance of bimodality in the atomic velocity distribution under a range of positive laser detuning and interaction time. This behavior corresponds to the formation of spatially distinct atomic clusters with unique momentum-position correlations, which are different from free expansion dynamics. In a magneto-optical trap laser setup, the cluster atoms form an expanding cubic lattice as the interaction time increases. This study advances our understanding of the Doppler heating mechanism and introduces the Rydberg-based velocimetry as a powerful tool for characterizing cold atomic systems.

References

[1] Arcizet, O., Cohadon, PF., Briant, T. et al. Radiation-pressure cooling and optomechanical instability of a micromirror. *Nature* **444** (2006). https://doi.org/10.1038/nature05244.

[2] Dai, Jinyu, et al. Laser cooling of a fermionic molecule. *Phys. Rev. Res* **6** (2024). https://link.aps.org/doi/10.1103/PhysRevResearch.6.033135.

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Magic wavelength traps for collective Rydberg excitations

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Strong, long-range interaction between Rydberg atoms plays an important role in many emerging fields of research, including the field of quantum optics, where the interactions are mapped onto photons that are propagating through or stored in the atomic medium as coherent atomic excitations. However, photon storage times are limited by various decoherence mechanisms, including thermal atomic motion and inhomogeneous differential light shifts between atoms sharing the excitation. The latter can be suppressed by magic trapping which equalizes the AC Stark shifts for the ground and excited levels of the atom.

On this poster, I present our implementation of a magic trap for ultracold Rydberg atoms. We conduct photon storage and retrieval measurements for two different trapping geometries: a magic lattice and a running wave trap with different trap wavelengths. Our experiments demonstrate that both the longitudinal standing wave and the radial trap shape impact the magic condition. This difference arises from the Rydberg electron wavefunction extending over a significant region of the trap potential and contributing a ponderomotive part to the trap potential. We investigate how this part scales with principle quantum number n and determine the optimal magic lattice wavelength for each Rydberg state [1].

Besides, I will also present our progress towards a new project on implementation of an EMCCD camera into the experiment. Our current goal is to use the low-photon level sensitive camera to experimentally measure the nonlinear optical response of a strongly interacting Rydberg atoms and demonstrate how this interaction is imprinted on the outgoing probe light.

References

[1] L. Ahlheit, Phys. Rev. A **111**, 013115 (2025)

Continuous operation of a coherent 3,000-qubit system

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Neutral atoms are a promising platform for quantum science, enabling advances in areas ranging from quantum simulations and computation to metrology, atomic clocks and quantum networking. While atom losses typically limit these systems to a pulsed mode, continuous operation could significantly enhance cycle rates, remove bottlenecks in metrology, and enable deep-circuit quantum evolution through quantum error correction. Here we demonstrate an experimental architecture for high-rate, continuous reloading and operation of a large-scale atom array system while realizing coherent storage and manipulation of quantum information. Our approach utilizes a series of two optical lattice conveyor belts to transport atom reservoirs into the science region, where atoms are repeatedly extracted into optical tweezers without affecting the coherence of qubits stored nearby. Using a reloading rate of 300,000 atoms in tweezers per second, we create over 30,000 initialized qubits per second, which we leverage to assemble and maintain an array of over 3,000 atoms for more than two hours. Furthermore, we demonstrate persistent refilling of the array with atomic qubits in either a spin-polarized or a coherent superposition state while preserving the quantum state of stored qubits. Our results pave the way for realization of large-scale continuously operated atomic clocks, sensors, and fault-tolerant quantum computers.

Fast entangling gates for Rydberg atoms via resonant dipole-dipole interaction

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The advent of digital neutral-atom quantum computers relies on the development of fast and robust protocols for high-fidelity quantum operations. In this work, we introduce a novel scheme for entangling gates using four atomic levels per atom: a ground-state qubit and two Rydberg states (see Fig. 1). A laser field couples the qubit to one of the two Rydberg states, while a microwave field drives transitions between the two Rydberg states, enabling a resonant dipole-dipole interaction between different atoms. We show that controlled-Z gates can be realized in this scheme without requiring optical phase modulation and relying solely on a microwave field with time-dependent phase and amplitude. We demonstrate that such gates are faster and less sensitive to Rydberg decay than state-of-the-art Rydberg gates based on van der Waals interactions. Moreover, we systematically stabilize our protocol against interatomic distance fluctuations and analyze its performance in realistic setups with rubidium or cesium atoms (see Fig. 2). Our results open up new avenues to the use of microwave-driven dipolar interactions for quantum computation with neutral atoms.

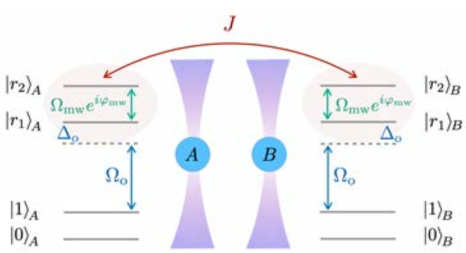

Figure 1. Atomic levels and driving.

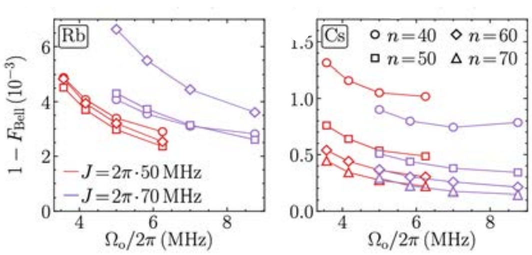

Figure 2. Infidelity at realistic parameters.

References

[1] G. Giudici, S. Veroni, G. Giudice, H. Pichler, J. Zeiher. arXiv:2411.05073. Accepted in PRX Quantum (2025).

Developing a Hybrid Tweezer Array of Laser-Coolable Dipolar Molecules and Rydberg Atoms

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Hybrid tweezer arrays filled with molecules and atoms offer new and exciting directions for quantum science and technology. The hybrid platform benefits strongly from the use of the unique properties of the two distinct species. Heteronuclear molecules possess a permanent electric dipole moment and a rich level structure with long coherence times, which is excellent for storing quantum information and exploiting quantum error correction schemes. Rydberg atoms, with their enormous induced electric dipole moments, allow enhanced long-range dipole-dipole interactions and can thus mediate spin-dependent interactions between distant molecules. This hybrid system therefore opens new opportunities for simulation with quantum networks and synthetic dimensions [1,2] as well as quantum computing with advanced protocols such as mid-circuit operations [3,4].

Here, we present our efforts to build such a hybrid tweezer array using ultracold CaF molecules and Rb atoms. We discuss the advantages and challenges of multispecies hybrid systems and present our schemes for preparing the ultracold molecules and atoms using direct laser-cooling techniques for both species. We further show our recent progress in cooling, loading, imaging and characterisation of the tweezer array. Finally, we present our ideas for loading both species into independent tweezer arrays using a dual-color tweezer approach and discuss our pathway for the Rydberg excitation for the multispecies dipole-dipole interactions.

References

[1] J. Dobrzyniecki *et al.*, Phys. Rev. A **108**, 052618 (2023)
[2] S. Dasgupta *et al.*, Phys. Rev. A **109**, 063322 (2024)
[3] C. Zhang *et al.*, PRX Quantum **3**, 030340 (2022)
[4] K. Wang *et al.*, PRX Quantum **3**, 030339 (2022)

Experimental Validation of the Influence of Control Noise on Fidelity

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Noise in control pulses is a ubiquitous problem in NISQ-era quantum computers. Here we experimentally study the relationship between control noise and qubit state fidelity and compare this to recent theoretical predictions [1]. We use our Ruby platform which contains a 10 x 10 tweezer array that is stochastically loaded from a Rb-85 MOT. We apply control signals in the form of a global microwave field featuring artificial noise and determine the resulting fidelity of the qubit operation. The resulting fidelity distributions are compared to theoretical predictions resulting from a stochastic Schrödinger equation treatment. In both cases we find characteristic behavior of fidelity versus noise duration for different types of noise, which are generally in good agreement. Simulation of gate operations using the stochastic Schrödinger equation therefore allows for a detailed treatment of the influence of control noise beyond average characteristics.

[1] R.J.P.T. de Keijzer, L.Y. Visser, O. Tse, and S.J.J.M.F. Kokkelmans, Phys. Rev. Res. 7, 023063 (2025)

Engineering Rydberg-mediated photon-photon interactions

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Photons interfere but do not interact. This lack of interaction plagues photon-based quantum information processing since one has to find some other way to create entanglement in a deterministic way. We aim to engineer interactions between photons by interfacing them with Rydberg atoms in a quasiparticle called a polariton. These polaritons inherit properties from both the photons and the atoms, which allows us to endow the photons with an effective interactions mediated by the Rydberg excitations.

In our experiment, we excite Rydberg polaritons in two dipole traps which we can arrange arbitrarily within a plane. With two separate Rydberg lasers, each dipole trap can be addressed separately. This allows us to write Rydberg polaritons with arbitrary Rydberg pair states. For an initial non-interaction pair state $|N\rangle = |N_1, N_2\rangle$ we can store and retrieve the polaritons from their respective traps. Driving a fast transition to a dipole-coupled, strongly interacting pair state $|I\rangle = |I_1, I_2\rangle$ then allows us to introduce an interaction between the polaritons – and switching the interactions off is equivalent to driving back to $|N\rangle$.

We have selected suitable candidates for the non-interacting and interacting pair states, but one of the transitions involved is in the THz range. We are therefore currently testing and benchmarking our THz source and study the coherent driving between Rydberg states of interest. We have recently observed Rabi oscillations on a THz transition and are now addressing different Rydberg states with our THz source to learn more about the device and the properties of the transitions involved. One current challenge is the low Rabi frequencies on the Thz transitions, which are in the 1-10 MHz range.

I will outline our general idea for the engineering of photon-photon interactions via Rydberg polaritons, give an update on the current status of the experiment and provide an outlook for our next steps towards that goal.

Towards Enhanced Loading of a NaCs Tweezer Array

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Tweezer arrays of ultracold polar molecules provide a promising platform for quantum simulation and quantum computation experiments. The long-distance dipole-dipole interactions and complex internal structure of molecules can be used to perform fast, high-fidelity quantum operations between long-lived states. In recent years, the Ni Group has assembled NaCs molecules in the motional ground state of optical tweezers, developed tools for coherent control of the molecule's rotational states, and demonstrated Bell state creation and an entangling gate. However, in the current assembly procedure, thermal excitations in the constituent atoms directly translate to lower molecular creation efficiency, resulting in few ground state molecules per experimental cycle. In pursuit of a highly filled array of several hundred molecules, we propose a new loading scheme leveraging recently developed shielding techniques and dynamic tweezer shaping to prepare ensembles of molecules in each tweezer and deterministically spill excess molecules. We discuss a new apparatus designed and constructed to implement this scheme, with a dual-chamber design and equipped with high-voltage in-vacuum electrodes. Finally, we demonstrate dual-species 2D and 3D MOTs in this new apparatus, as well as a tweezer array and progress towards loading ultracold ensembles in tweezers.

References

[1] Picard, L.R.B., Nature 637, 821–826 (2025)
[2] Picard, L.R.B., PRX Quantum 5, 020344 (2024)
[3] Park, A. J., Phys. Rev. Lett. 131, 183401 (2023)

A new quantum computing platform based on Yb atoms in optical tweezer arrays

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Alkaline earth-like atoms are promising candidates for the next-generation fault-tolerant quantum computing platforms. We are currently developing a new experiment based on fermionic 171Yb atoms in programmable arrays of optical tweezers. Optical tweezer arrays offer a platform in which the geometry of the atoms can be arbitrarily reconfigured by programming the phase mask imprinted on the tweezer laser beam using a spatial light modulator (SLM). Rapid rearrangement of atoms within the tweezer array sites can also be performed using a pair of acousto-optic deflectors (AODs). The two nuclear spin states of 171Yb will be used as robust and long-lived qubits, with the metastable clock state offering the possibility of implementing quantum error correction protocols, exploiting ground and metastable states as ancilla and data qubits. Multiqubit gates will be implemented via state-selective coupling to Rydberg states.

An apparatus for millimeter-wave-mediated quantum gates between Rydberg atoms

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Rydberg atom arrays have become a leading platform for quantum computing and simulation. However, the power-law decay of the interaction strength in Rydberg systems poses a limitation to efficient generation of long-range entanglement. We propose to trap Rydberg atoms in a millimeter (mm)-wave Fabry-Perot cavity to enable high-fidelity non-local entangling gates. Coupling a transition between circular Rydberg states to a cavity mode will enable atoms to interact with each other regardless of their locations, by emitting and reabsorbing photons to and from the cavity mode. We are developing a high-finesse superconducting cavity with optical access for atom trapping and single-atom detection in a cryogenic apparatus. The measured cavity finesse of $F = 5.8 \times 10^7$ at a temperature $T \approx 1K$ will allow for operating deep in the strong coupling regime, with single-atom cooperativity $C = 3 \times 10^6$ for circular Rydberg states. This new platform will enable entangling gates between atom pairs separated by millimeter-scale distances, as well as scalable preparation of many-body entangled states. The platform also offers opportunities in quantum simulation, with the interplay of global cavity-mediated interactions and local dipolar interactions raising prospects for accessing novel strongly correlated states. I will touch on progress towards near-term quantum-simulations with dipolar spin-exchange interactions in a free-space tweezer array, in addition to presenting the design of the cryogenic apparatus for trapping atoms within the superconducting cavity.

Reference

[1] T. Zhang, M. Wu, S. R. Cohen, L. Xin, D. Das, K. K. S. Multani, N Peard, A-M Valente-Feliciano, P. B. Welander, A. H. Safavi-Naeini, E. A. Nanni, and M. Schleier-Smith. Optically accessible high-finesse millimeter-wave resonator for cavity quantum electrodynamics with atom arrays. arXiv preprint arXiv:2506.05804 (2025)

Towards Neutral Atom Quantum Computing with Trapped Yb-171 Atoms

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Experimental studies of quantum information processing are essential for advancing quantum computing and for exploring the broader potential of quantum technologies. Neutral atoms, due to their intrinsic uniformity and scalability, are a compelling platform for quantum computing. Among them, the fermionic isotope Ytterbium-171 stands out as an excellent qubit candidate, thanks to its spin-½ nuclear ground state and long-lived optical clock states that offer multiple robust options for qubit encoding. Interactions between qubits can be mediated via Rydberg excitations, enabling entangling operations essential for universal quantum computing.

We have developed a working experimental platform that traps individual Ytterbium-171 atoms in optical tweezers generated using an acousto-optic deflector (AOD) and have successfully demonstrated high-fidelity single-qubit gates on the nuclear spin ground state. To enhance flexibility and scalability, we are currently upgrading our system with static tweezer arrays generated by a spatial light modulator (SLM), combined with dynamically reconfigurable tweezers from an AOD. We are also implementing coherent operations on the optical clock transition to enable an additional high-coherence qubit basis, as well as Rydberg excitation to realize two-qubit entangling gates—together completing the universal gate set required for general quantum computation.

Looking ahead, our platform will provide a versatile testbed for exploring quantum information protocols, including quantum algorithms and foundational demonstrations of quantum error correction.

Dual-type dual-element atom arrays for quantum information processing

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Neutral-atom arrays are a leading platform for quantum technologies, offering a promising route toward large-scale, fault-tolerant quantum computing. However, several challenges remain in this platform, including low experimental repetition rate, reconfigurable individual addressability and rapid, non-demolition, site-selective readout. To address these limitations, we are developing a novel quantum processing architecture based on dual-type, dual-element Yb-Rb atom arrays, where individually trapped Yb atoms serve as data qubits, and small Rb atomic ensembles enable ancillary operations. By leveraging the selective initialization, coherent control, and collective optical response of atomic ensembles, we have designed ensemble-assisted quantum operations that enable reconfigurable, fast control of individual data qubits and rapid mid-circuit readout, including both projective single-qubit and joint multi-qubit measurements. Moreover, we will implement continuous reloading atoms from 3D magneto-optical trap to optical tweezer arrays to address atom loss during quantum processing, which will reduce the experimental cycle time. These capabilities open new pathways toward scalable, fault-tolerant quantum computation, enabling repetitive error syndrome detection and efficient generation of long-range entangled many-body states, thereby expanding the quantum information toolbox beyond existing platforms.