

CATMIN

The Cold Atom Molecule Interactions – CATMIN conference is a biannual event, whose previous editions were held in Paris (France), Waterloo (Canada), and London (UK). CATMIN IV will cover all areas of Rydberg physics from quantum sensing, computing and simulation to precision spectroscopy and cold chemistry.

CATMIN IV Organizing Committee

- Rosario González-Férez (Universidad de Granada, Granada, Spain)
- Luis Marcassa (University of Sao Paulo, São Paulo, Brazil)
- James Shaffer (Quantum Valley Ideas Laboratories, Waterloo, Canada)

Local Organizing Committee

- Rosario González-Férez, Universidad de Granada.

Practical information

The CATMIN IV conference will be held at the Facultad de Ciencias of the Universidad de Granada:

- Scientific sessions: Salón de Grados.
- Posters: Hall.
- Lunches and coffee breaks: Hall.



Social events:

- Reception at the Gardens of Carmen de la Victoria on May 20th at 19:00.
- Alhambra Guided Tour on May 23rd for registered participants.
- Conference dinner at La Chumbera on May 22nd at 20:00.



Program

Tuesday, May 20th

19:00 - 21:00 Registration and reception at the Gardens of Carmen de la Victoria.

Wednesday, May 21st

8:00 - 8:30 Registration at the Hall of Facultad de Ciencias.

8:30 - 9:00 Opening at Salon de Grados

09:00 – 09:30 Mark Saffman
Towards higher fidelity Rydberg gates and two-species entanglement.

09:30 – 10:00 Antoine Browaeys
Quantum magnetism using Rydberg atoms with dipolar interactions.

10:00 – 10:20 Yuechun Jiao
Suppression of Motional Dephasing of Rydberg W State by Using State Mapping.

10:20 – 10:40 Aaron Reinhard
Coherent Manipulation of Three-Atom Entangled States Near Förster Resonance.

10:40 - 11:20 Coffee break.

11:20 – 11:50 Frédéric Merkt
Precision Rydberg spectroscopy in H, He and H₂.

11:50 – 12:20 Harald Kübler
Spatially Resolved Stark Measurements in Nitric Oxide using a Three Photon Excitation Scheme for a Trace Gas Sensor.

12:20 – 12:40 Luis G. Marcassa
Phase transition observed by transmission spectroscopy in cold Rydberg atoms.

12:40 – 13:00 Hela Ladjimi
Radioactive RaAg⁺ molecular ion: electronic structure, formation schemes, and prospects for precision measurements.

13:00 - 15:00 Lunch

Wednesday, May 21st (continuation)

- 15:00 – 15:30 Doerte Blume
Forces on alkali Rydberg atoms due to non-linearly polarized light.
- 15:30 – 16:00 Stephen Hogan
Interfacing microwave-dressed Rydberg atoms with superconducting circuits.
- 16:00 – 16:20 Tibor Jónás
Multi-Channel Quantum Scattering Calculation of fine structure quenching and electronic excitation exchange between ultracold meta-stable Sr^+ and ground state Rb atoms.
- 16:20 – 17:00 Coffee Break
- 17:00 – 17:30 Peter Schmelcher
Rydberg physics: From Ultralong-Range Molecules to Quantum Simulation and Quantum Optimization.
- 17:30 – 17:50 Matthew Eiles
Precision spectroscopy and vibrational stabilization of trilobite Rydberg molecules.
- 18:00 – 20:00 Poster session. Drinks and Snacks.

Thursday, May 22nd

- 09:00 – 09:30 Jaewook Ahn
Rydberg atom collision by fly-by interaction gates.
- 09:30 – 10:00 Johannes Zeiher
Quantum computing with metastable strontium qubits.
- 10:00 – 10:20 Malte Schlosser
Quantum Technology Platform Beyond 1000 Atomic Qubits for Quantum Simulation, Computation, and Metrology.
- 10:20 – 10:40 Hugo Tortel Kepa
Rydberg thermometry in a Sr Optical Lattice Clock.
- 10:40 – 11:20 Coffee Break
- 11:20 – 11:50 Hossein R. Sadeghpour
Ask what a Rydberg atom can do for your polar molecule.
- 11:50 – 12:20 Igor Lesanovsky
Quantum simulation of molecular processes with trapped Rydberg atoms and ions.
- 12:20 – 12:40 Tangi Legrand
Ultralong-Range Ytterbium Rydberg Molecules.
- 12:40 – 13:00 Alexander Guttridge
Exploring ultracold Rydberg and molecular systems using two-species optical tweezer arrays.
- 13:00 – 15:00 Lunch
- 15:00 – 15:30 Michel Brune
Quantum-Non-Demolition Detection of Circular Rydberg Atom.
- 15:30 – 16:00 Guido Pupillo
Towards efficient quantum error correction with neutral atoms.
- 16:00 – 16:20 Lorenzo Festa
Towards quantum computation with Sr88 atom arrays.
- 16:20 – 17:00 Coffee Break
- 17:00 – 17:30 Georg Raithel
Electric-field measurement in cold ion streams and in inductively coupled plasma.
- 17:30 – 17:50 Edward Grant
Self-organized criticality and prethermalization in the nitric oxide molecular ultracold plasma.
- 20:00 - CATMIN-IV dinner: La Chumbera (Camino de Sacromonte, 107, 18010, Granada)

Friday, May 23rd

- 09:00 – 09:30 C. Stuart Adams
Rydberg applications: vortex beams and qudits.
- 09:30 – 10:00 Givanna Morigi
Controlling quantum trajectories with quantum fields.
- 10:00 – 10:20 Johannes Deiglmayr
Realization of topological Thouless pumping in a synthetic Rydberg dimension.
- 10:20 – 10:40 Eva Casotti
Rotating dipolar supersolids.
- 10:40 – 11:10 Coffee Break
- 11:10 – 11:40 Steven L. Rolston
Atomic Ensembles with Rydberg Excitations.
- 11:40 – 12:10 Thomas Pohl
Quantum continuous time crystals in dissipative Rydberg-atom arrays.
- 12:10 – 12:30 Louise McCaul
Rydberg-atom interferometry and electrometry for tests of positronium gravity.
- 12:30 – 12:50 James P. Shaffer
Towards a Portable Two-Photon Cesium Optical Clock.
- 12:50 – 14:30 Lunch
- 15:30 – Alhambra Group 1.
Meeting point: C. Real de la Alhambra, Granada, Ticket office
- 15:30 – Alhambra Group 2.
Meeting point: C. Real de la Alhambra, Granada, Ticket office



Wednesday's Abstracts

Towards higher fidelity Rydberg gates and two-species entanglement

Mark Saffman

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High fidelity Rydberg mediated entanglement with fidelity $> 99\%$ has been demonstrated with four atomic elements: Rb, Cs, Sr, Yb. For future quantum computing applications even higher fidelity is needed. I will describe work in progress towards higher fidelity based on one-photon excitation of Cs atoms. Using two different atomic elements independent control and measurements are straightforward which is valuable for scalable architectures for quantum error correction. We have demonstrated a novel approach to trapping interleaved two-species arrays[1] and ongoing work will be presented which has achieved two-species entanglement.

References

- [1] C. Fang, J. Miles, J. Goldwin, M. Lichtman, M. Gillette, M. Bergdolt, S. Deshpande, S. A. Norrell, P. Huft, M. A. Kats, and M. Saffman, *Interleaved dual-species arrays of single atoms using a passive optical element and one trapping laser*, arXiv:2412.20261 (2024)

Quantum magnetism using Rydberg atoms with dipolar interactions

*Antoine Browaeys**

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This talk will present our recent experiments using the resonant dipole interaction between Rydberg atoms in tweezer arrays to implement many-body spin Hamiltonians. We first explore quantum magnetism of the XY, spin 1/2 model in a 1D ring [arXiv:2501.08179]. This spin model can be described in terms of the Tomonaga-Luttinger liquid formalism. We assess in our experiment how accurate the mapping is by preparing the ground state of the system, as well as exploring its out-of-equilibrium properties. Second, we use three Rydberg states in each atom to implement a bosonic version of the t-J model, usually introduced to describe the properties of doped magnets. We observe the binding of holes and explore kinetic frustration in a ladder geometry [arXiv:2501.08233].

Suppression of Motional Dephasing of Rydberg W State by Using State Mapping

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Maintaining the coherence in quantum systems is interesting in both fundamental physics [1] and quantum information processing [2]. In particular, suppressing the dephasing caused by thermal fluctuations in quantum systems can potentially enable functional quantum devices. In this talk, we present suppressing the motional dephasing of Rydberg W State by creating an a priori unknown but correct phase to each Rydberg atom in an ultracold atomic ensemble [3]. We firstly present our model, π -wait- π protocol, where the phase created is exactly proportional to the unknown velocity of the thermal motion, resulting in a condition as if no thermal motion occurs to the Rydberg atom upon the retrieval of the signal photon. In the experiment, we prepare the Rydberg W state using EIT storage and demonstrate the validity of our π -wait- π protocol by measuring the retrieval single signal photon. In Fig. 1, we display the retrieval photons for free decay and for using π -wait- π protocol, showing that the coherence storage time of Rydberg W state can be enhanced one order of magnitude with our protocol compared to the case of free decay. Our theory shows that, for no atom loss, and minimal laser or electromagnetic noise, the motional dephasing will be completely suppressed. In this case, Rydberg-state decay remains as the only dephasing channel.

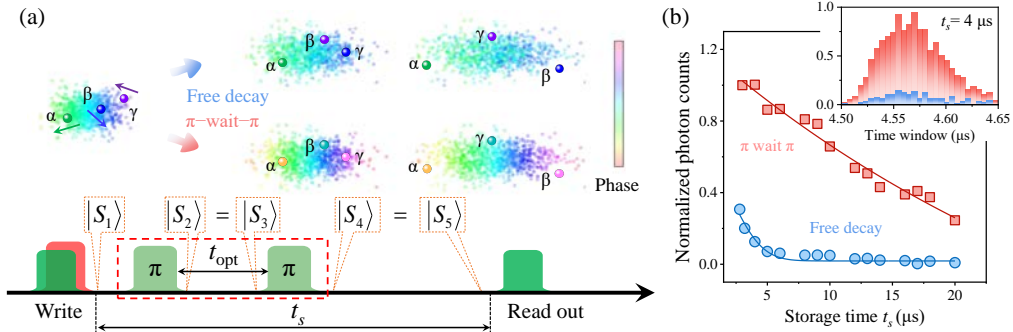


Figure 1: (a) Illustration of keeping phase of Rydberg W state with π -wait- π protocol. (b) Comparison of retrieval photons for free decay (circles) and π -wait- π protocol (squares).

References

- [1] Z. K. Mineev, S. O. Mundhada, S. Shankar, P. Reinhold, R. Gutiérrez-Jáuregui, R. J. Schoelkopf, M. Mirrahimi, H. J. Carmichael, and M. H. Devoret, *Nature (London)* **570**, 200 (2019).
- [2] D. Bluvstein et al., *Nature (London)* **626**, 58 (2024).
- [3] Yuechun Jiao, Changcheng Li, Xiao-Feng Shi, Jiabei Fan, Jingxu Bai, Suotang Jia, Jianming Zhao, and C. Stuart Adams, *Phys. Rev. Lett.* **134**, 053604 (2025).

Coherent Manipulation of Three-Atom Entangled States Near Förster Resonance

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Neutral atoms in low-lying states make excellent qubits. They interact weakly and are insensitive to environmental perturbations. However, to generate entanglement one must make the atoms interact strongly. This is usually done by promoting them to Rydberg states. Most experiments use Rydberg-Rydberg interactions in the van der Waals regime, as near-resonant interactions can lead to unwanted energy exchange and decoherence. Nonetheless, interaction resonances can present an opportunity. Here, I outline a method for generating entanglement by promoting atoms to Rydberg levels near Förster resonance [1]. The resulting three-atom states can be driven coherently, even in an unstructured bulk gas [2]. I will present evidence for coherent evolution, as well as preliminary data on the coherence time.

References

- [1] T. Pohl and P. R. Berman, Phys. Rev. Lett. **102**, 013004 (2009)
- [2] Tomohisa Yoda, Emily Hirsch, Jason Montgomery, Dilara Sen, Aaron Reinhard, Phys. Rev. A **107**, 062818 (2023)

Precision Rydberg spectroscopy in H, He and H₂

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High-resolution spectroscopic measurements in few-electron atoms and molecules are increasingly used as a means to test the foundations of the theory of atomic and molecular structure. Modern first-principles calculations of the energy-level structure of few-electron atomic and molecular systems consider all interactions in the realm of the standard model of particle physics (see, e.g., Refs. (1)-(4)). Systematic comparisons of the results of such calculations with precise spectroscopic measurements in simple atoms and molecules such as H, He, and H₂⁺ aim at searching for effects not yet included in the theory (see, e.g., Refs. (5) and (6)) and at reducing the uncertainties of physical constants (see, e.g., Refs. (7) and (8)).

This talk will present precision spectroscopic measurements of transitions to high Rydberg states of H, He, and H₂, which we use to determine accurate values of their ionization energies and, in the case of H₂, also of the spin-rovibrational energy-level structure of H₂⁺. The talk will describe our experimental strategy to overcome limitations in the precision and accuracy of the measurements originating from the Doppler effect, the Stark effect, and the laser-frequency calibration. Experimental results on all three systems will then be compared with the results of first-principles calculations that include the treatment of finite-nuclear-size effects and relativistic and quantum-electrodynamics corrections up to high order in the fine-structure constant. Recent aspects of these investigations include a new determination of the Rydberg constant (Ref. (9)) as a contribution to the resolution of the proton-size puzzle (see Ref. (10)), a new method to record Doppler-free single-photon excitation spectra in the visible and UV spectral ranges (Ref. (11)), a “zero-quantum-defect” method to determine the energy-level structure of homonuclear diatomic molecular ions such as H₂⁺ (Ref. (12)), and a 9σ discrepancy between theory and experiment in the ionization energies of metastable (1s2s ³S₁) ³He and ⁴He (Refs. (3) and (13)).

References:

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- (2) V. Korobov, L. Hilico and J.-Ph. Karr, *Phys. Rev. Lett.* **118**, 233001 (2017)
- (3) V. Patkós, V. A. Yerokhin, and K. Pachucki, *Phys. Rev. A* **103**, 042809 (2021)
- (4) M. Puchalski, J. Komasa, P. Czachorowski, and K. Pachucki, *Phys. Rev. Lett.* **122**, 103003 (2019)
- (5) C. Delaunay *et al.*, *Phys. Rev. Lett.* **130**, 121801 (2023)
- (6) M. Germann *et al.*, *Phys. Rev. Res.* **3**, L022028 (2021)
- (7) A. Grinin *et al.*, *Science* **370(6520)**, 1061–1066 (2020)
- (8) S. Schiller, J.-Ph. Karr, *Phys. Rev. A* **109**, 042825 (2024)
- (9) S. Scheidegger, and F. Merkt, *Phys. Rev. Lett.* **132**, 113001 (2024)
- (10) A. Antognini *et al.*, *Science* **339(6118)**, 417–420 (2013)
- (11) G. Clausen, S. Scheidegger, J. A. Agner, H. Schmutz, and F. Merkt, *Phys. Rev. Lett.* **131**, 103001 (2023)
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- (13) G. Clausen, K. Gamlin, J. A. Agner, H. Schmutz, and F. Merkt, *Phys. Rev. A* **111**, 012817 (2025)

Spatially Resolved Stark Measurements in Nitric Oxide using a Three Photon Excitation Scheme for a Trace Gas Sensor

Fabian Munkes,¹ Alexander Trachtmann,¹ Patrick Kaspar,¹ Yannick Schellander,² Florian Anschutz,¹ Ettore Eder,¹ Lars Baumgärtner,³ Philipp Hengel,³ Jens Anders,³ Norbert Fruehauf,² Robert Löw,¹ Tilman Pfau,¹ and Harald Kübler¹

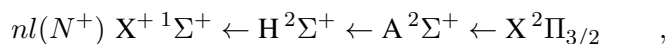
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At the beginning of the 1990s it was known, that nitric oxide (NO) plays an important role as a signaling molecule in the mammalian system, and a change of its concentration in the exhaled breath may indicate certain diseases. We showed in a proof-of-concept experiment the operation of a NO trace-gas sensor at ambient pressure at a concentration of 10 ppb.

Our detection principle is based on the electronic amplification of a current generated by free charges resulting from collisions of NO molecules in a Rydberg state with background particles. For the excitation we use continuous-wave (cw) laser systems for the transitions



which are at about 226 nm, 540 nm and 835 nm, respectively.

We investigated the collisional shift and line broadening of Rydberg states in nitric oxide (NO) with increasing density of a background gas at room temperature [1]. As a background gas, we either use NO itself or nitrogen (N₂) and identify pressures for an optimal operation of our sensor.

We measured Stark Maps to investigate optimized electric fields for our NO detection and extracted improved values for the quantum defects of the rotational ground state ($N^+ = 0$). In these measurements, we saw unshifted lines not explained by theory [2].

In this presentation, we show spatially resolved Stark Maps pointing towards areas close to the cell wall with a strongly suppressed electric field.

References

- [1] Fabian Munkes, Alexander Trachtmann, Patrick Kaspar, Florian Anschutz, Philipp Hengel, Yannick Schellander, Patrick Schalberger, Norbert Fruehauf, Jens Anders, Robert Löw, Tilman Pfau, and Harald Kübler. Collisional shift and broadening of Rydberg states in nitric oxide at room temperature. *Phys. Rev. A*, 109:032809, Mar 2024.
- [2] Fabian Munkes, Matthew H. Rayment, Alexander Trachtmann, Florian Anschutz, Ettore Eder, Philipp Hengel, Yannick Schellander, Patrick Schalberger, Norbert Fruehauf, Jens Anders, Robert Löw, Tilman Pfau, Stephen D. Hogan, and Harald Kübler. High-Resolution Continuous-Wave Laser Spectroscopy of Long-Lived Rydberg States in NO. *The Journal of Physical Chemistry Letters*, 15(40):10171–10180, 2024.

Phase transition observed by transmission spectroscopy in cold Rydberg atoms

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We have investigated phase transition using transmission spectroscopy of Rydberg atoms held in a magneto-optical trap, placed inside a customized microwave cavity. Rydberg atomic states are excited in a two-photon process. The first photon, at 780 nm, couples the ground state ($5S_{1/2}$) to an intermediate state ($5P_{3/2}$), and it is defined as the probe laser. The second photon, at 480 nm, couples the intermediate state ($5P_{3/2}$) to the Rydberg state ($nS_{1/2}$ for $57 \leq n \leq 67$). By observing the probe laser beam transmission as a function of the coupling laser frequency, we were able to measure Rydberg excitations of about 1-2% of the total sample. These results represent an improvement compared to our recent work [1]. The phase transition frequency is measured as a function of the 480 nm laser intensity as well as the principal quantum number. We have also investigated the phase transition frequency dependence with microwave power, at 13.053 GHz, which is resonant with the transition. Such a system may advance Rydberg-based sensors and other quantum technologies.

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References

- [1] *J. D. Massayuki Kondo et al. Multiphoton-dressed Rydberg excitations in a microwave cavity with ultra-cold Rb atoms. Phys. Rev. A 110, L061301 (2024)*

Radioactive RaAg^+ molecular ion: electronic structure, formation schemes, and prospects for precision measurements

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We present a theoretical investigation of the formation of the radioactive molecular ion RaAg^+ . As a basis for comparison, we first conducted a systematic study of the electronic structure of the $X^1\Sigma$ ground state of radium-alkali-metal molecular ions, RaAlk^+ (Alk = Li, Na, K, Rb, Cs and Ag). The ground-state potential energy curves and permanent dipole moments (PDMs) are computed using high-level quantum chemistry methods, specifically the coupled cluster approach with single, double, and perturbative triple excitations [CCSD(T)], in combination with large Gaussian basis sets and small-core relativistic energy-consistent pseudopotentials. Subsequently, we determined the excited state potential energy curves and dipole moments of eight λ -S states and fourteen Ω states for RaAg^+ using the multireference configuration interaction method with Davidson correction (MRCI+Q). The spectroscopic parameters of the bound states are extracted, and spin-orbit coupling effects are explicitly accounted for in our calculations. Additionally, we employed coupled-channel calculations to estimate the nearest-neighbor density of magnetic-field-induced Feshbach resonances in ultracold $\text{Ra}^+ + \text{Ag}$ collision systems. The present results may be useful for creating a quantum simulator using ultracold Ra^+ ions and Ag atoms.

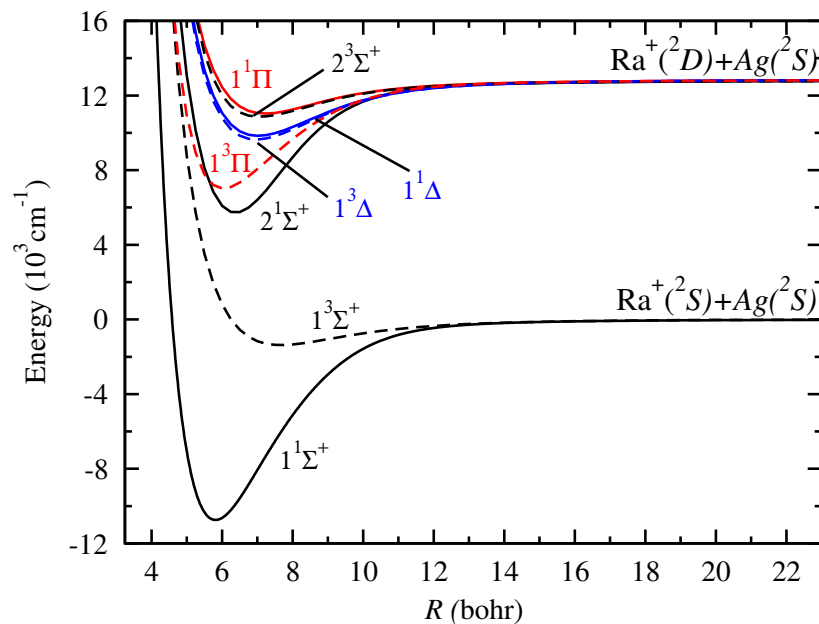


Figure 1: Potential energy curves for the ground and excited states using MRCI+Q and aug-cc-pwCV5Z.

Acknowledgments

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Forces on alkali Rydberg atoms due to non-linearly polarized light

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Trapped Rydberg atoms are highly promising candidates for quantum science experiments. While several approaches have been put forward to exert (trapping) forces on isolated Rydberg atoms, a widely applicable lossless technique is lacking. We propose a robust versatile alternative technique that avoids lifetime compromising losses. Our proposal leverages the vector polarizability, which is induced by non-linearly polarized light and is shown to be several orders of magnitude larger than the usual scalar and tensor polarizabilities for commonly used alkali Rydberg series such as the nS , nP , and nD series with principal quantum number n as low as 30. The resulting force can be used to trap isolated Rydberg atoms over long times, which constitutes a key advance that is expected to impact quantum simulation applications, as well as to generate large light–Rydberg-atom hybrid states, which possess non-trivial position-dependent forces.

Interfacing microwave-dressed Rydberg atoms with superconducting circuits

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Coherent interfaces between Rydberg atoms and superconducting microwave circuits offer opportunities for the realisation of long-range optically coupled networks of superconducting qubits, and the implementation of long-coherence-time atomic quantum memories for superconducting processors [1]. The successful realisation of such interfaces requires careful management of effects of stray electric fields close to the cryogenically cooled superconducting-chip surfaces [2, 3]. Contributions from these stray fields can be minimised through the choice of atomic species used in the experiments [4], or the application of strong offset electric fields that dominate over these stray fields [5]. From these starting points, further control and tunability of the Rydberg-Rydberg transitions in this setting can be achieved through the addition of microwave dressing fields [6, 7]. In this talk, I will describe experiments in which we interface Rydberg helium atoms with a chip-based superconducting co-planar waveguide (CPW) microwave resonator. I will show how two-colour two-photon transitions between the triplet 55s and 56s Rydberg states, in which one photon at 19.55 GHz is supplied by the resonator and the other by a strong microwave control field, can be used to realise a robust tuneable interface. I will also show how the differential polarizability, and hence dc Stark shift of the transition between these states can be eliminated at this interface through the application of a second strong microwave dressing field [8]. Finally, I will show how, in a separate set of experiments, a strong single-photon transition between the triplet 50s and 50p Rydberg states in helium can be resonantly coupled to the 11.75 GHz mode of a CPW resonator by exploiting the AC Stark shift induced by an additional strong microwave dressing field. These results, represent key steps toward the single-photon strong-coupling regime at this hybrid quantum interface.

References

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Multi-Channel Quantum Scattering Calculation of fine structure quenching and electronic excitation exchange between ultracold meta-stable Sr^+ and ground state Rb atoms

Tibor Jónás^{1,2,3,*}, *Romain Vexiau*³, *Nadia Bouloufa-Maafa*³, *Eliane Luc-Koenig*³, *Andrea Orbán*² and *Olivier Dulieu*³

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Our work is related to ongoing hybrid trap experiments, where usually a single ion is injected in the middle of an atomic gas cloud. We focus on the theoretical modelling of the dynamics of ion-neutral system at ultra low temperature ($\ll 1\text{K}$) in order to design ways for their full quantum control. In the experiments alkaline earth ion and alkali atom are used. Due to the laser cooling scheme a metastable d-level of the ion is considerably populated in the experiments, e.g. in the case of $^{88}\text{Sr}^+$ ion embedded in the ultracold ^{87}Rb atomic cloud [1] or $^{138}\text{Ba}^+$ in ^6Li cloud [2, 3]. Due to the large internal energy of the ion several inelastic processes can take place, like charge-exchange (CE), fine structure quenching (FSQ) or electronic excitation exchange (EEE). We perform detailed atomic and molecular structure calculations and we perform dynamical calculations based on the multi-channel quantum scattering (MCQS) description of the collision between an ion and atom. Hund's case (a) potential energy curves, rotational and spin-orbit couplings are involved in our theoretical description. We determine state-to-state cross sections and rate coefficients, which can be compared to experimental ones.

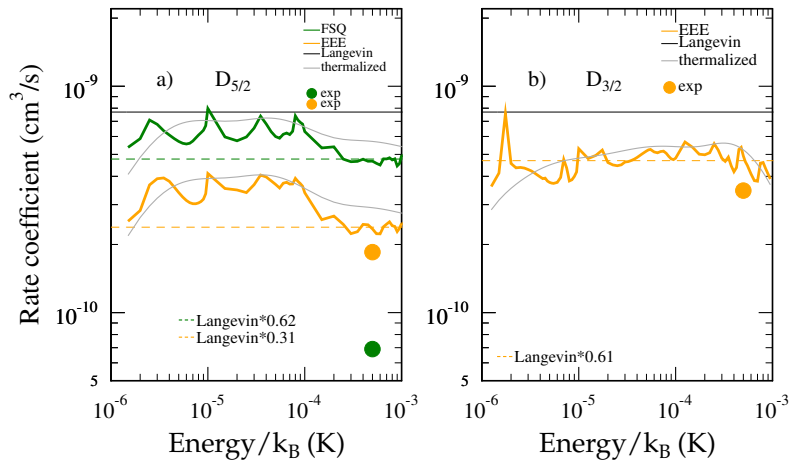


Figure 1: Computed rate coefficients (colored solid lines) for the FSQ and EEE process as a function of the temperature in the ultracold collision between ground state ^{87}Rb atom and excited $^{88}\text{Sr}^+$ ion for incoming channel $\text{Rb}(5s^2S_{1/2})+\text{Sr}^+(5d^2D_{3/2,5/2})$. The result is in good agreement with the experiment of [1] (full circles) is very satisfactory: it demonstrates the high quality of our computed molecular data, and it demonstrates the strong coupling between the rotation and internal angular momenta of the reactants even in the ultracold regime, fully implemented in our quantum scattering approach.

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Rydberg physics: From Ultralong-Range Molecules to Quantum Simulation and Quantum Optimization

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A review on the most recent activities in Rydberg physics at the center for optical quantum technologies will be provided. I start out with addressing the exotic properties of ultralong-range Rydberg molecules (ULRM). ULRM possess extreme bond lengths of the order of several micron and huge dipole moments. Their potential energy curves mimic the highly oscillatory structure of the Rydberg wave function thereby offering new possibilities for engineering molecular properties on vastly different time and length scales. Trilobite and butterfly states can easily be controlled by weak external electric or magnetic fields. I demonstrate that synthetic dimensions based on quantum numbers can be used to design conical intersections and consequently non-adiabatic interaction effects in the spectra of ULRMs. Ultrafast decay processes are a consequence of these intersections. Quenches of external fields then lead to a rich rovibrational quantum dynamics of ULRM.

The second part of this talk focuses on quantum simulation and quantum optimization. I provide evidence for novel quantum phases of strongly interacting many-body Rydberg setups, specifically the so-called bond order density wave is unraveled and the extended control of Luttinger liquid phases is presented. On the quantum optimization side I describe how a local detuning approach can enhance the tweezer array-based control of the famous graph theoretical MIS and Max-Cut problems. The traditional order $\propto N^2$ approach is here replaced by a linear system size scaling approach. Finally, I will make a short excursion into our recent work on single atom implementation of integer linear programming. Here, a single Rydberg atom will be used to encode linear and even nonlinear integer problems which are known to be difficult to solve in a classical manner.

Precision spectroscopy and vibrational stabilization of trilobite Rydberg molecules

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In this talk, I report on a joint experimental-theoretical work in which we perform three-photon photoassociation to obtain high resolution spectra of ^{87}Rb trilobite dimers for the principal quantum numbers $n = 22, 24, 25, 26$, and 27 . The large binding energy of the molecules in combination with a relative spectroscopic resolution of 10^{-4} provides a rigorous benchmark for existing theoretical models. A recently developed Green's function framework, which circumvents the convergence issues that afflicted previous studies, is employed to theoretically reproduce the vibrational spectrum of the molecule with high accuracy. With this, we extract the 3S_1 scattering phase shift with unprecedented accuracy, at low energy regimes inaccessible to free electrons [1]. Additionally, for $n = 25$, we observe a regularly spaced series of highly excited ($\nu \sim 100$) vibrational states close to the dissociation threshold. The existence and observed stability of these states requires the almost complete suppression of the adiabatic decay pathway induced by the P -wave shape resonance of Rb. This stabilization is predicted to occur only for certain Rydberg levels where the avoided crossing between trilobite and P -wave dominated butterfly potential energy curves nearly vanishes, allowing the vibrational states to diabatically traverse the crossing with almost unit probability. This is the first direct measurement of beyond-Born-Oppenheimer physics in long-range Rydberg molecules, and paves the way for future experiments to access and manipulate wavepackets formed from high-lying vibrational states [2].

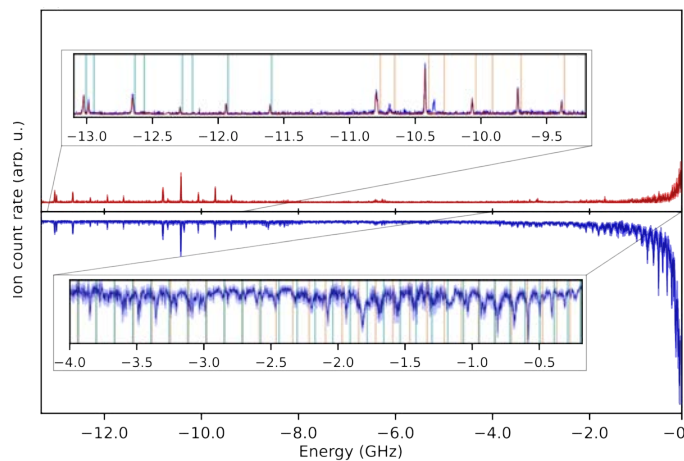


Figure 1: Experimental and theoretical spectrum for an $n = 25$ trilobite molecule, showing both the deeply bound molecular states utilized for precision extraction of scattering phase shifts (upper panel) and the vibrationally excited series stabilized by non-adiabatic coupling (lower panel).

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Thursday's Abstracts

Rydberg atom collision by fly-by interaction gates

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Recent advancements have enabled neutral atom qubits to transition from static to dynamic systems [1], enhancing their mobility and connectivity. Techniques such as atom throwing and catching [2] using optical tweezers suggest that atomic qubits can serve as both processing units and information carriers, effectively functioning as flying qubits. In this presentation, we introduce a method for generating entanglement as atoms fly by each other. We demonstrate that flyby Rydberg interactions induce entanglement between atomic states during flight, with the degree of entanglement dependent on velocity and closest approach in distant collisions. As an application of this collisional entanglement, we propose a time-efficient flyby controlled-Z (CZ) gate, where entanglement generated during flight can effectively implement multiple CZ gates from a single atomic release. Our study provides experimental evidence that interactions between flying atomic qubits can serve as a useful tool, paving the way for fast gate operations in neutral atom quantum computing.

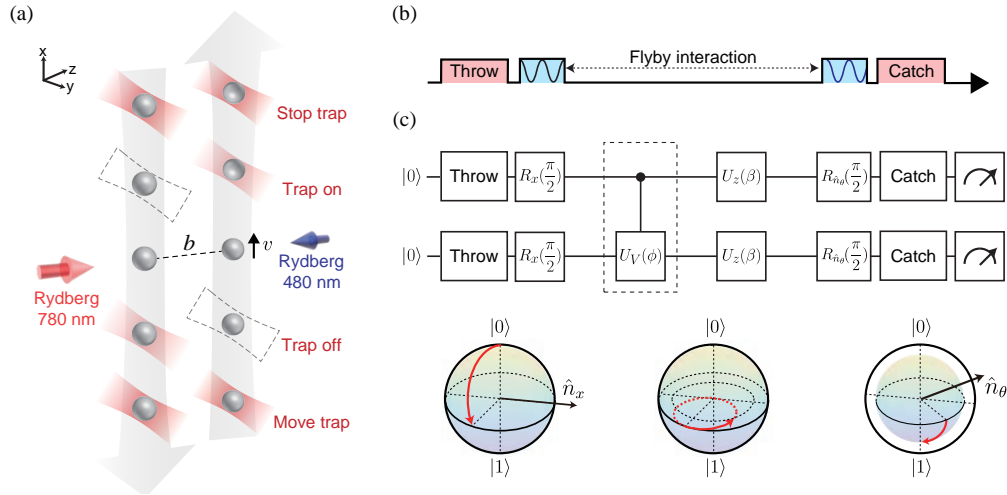


Figure 1: (a) A schematic representation of the flyby interaction. An atom, transported by optical tweezers, moves with velocity v and interacts with another atom traveling in the opposite direction. Rydberg beams facilitate excitation to the Rydberg state and enable state manipulation. (b) A timing diagram of the experimental sequence, illustrating the energy level shift during the throw-and-catch process, along with the $\pi/2$ -Rydberg pulses. The interaction phase accumulated during the flyby, represented as $\int V(t)dt$, captures the phase acquired during the collision. (c) A quantum circuit diagram depicting the experimental protocol. The circuit comprises initial rotations $R_x(\pi/2)$, an interaction-induced phase shift $U_V(\phi)$, and final state rotations $U_z(\beta)$ and $R_{\hat{\beta}}(\pi/2)$, followed by detection.

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Quantum computing with metastable strontium qubits

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Atom arrays have shaped the research frontier in quantum simulation, quantum metrology and quantum computation in recent years. In this talk, I will present our approach to realizing an atom array platform based on directly loaded large-scale optical lattices. Utilizing a specialized, highly anisotropic lattice geometry, we directly load thousands of individually addressable strontium atoms from the magneto-optical trap. We demonstrate high-fidelity and low-loss imaging [1] and show how iterative assembly as well as continuous operation of atom arrays is possible in our architecture [2]. For applications in quantum computing and quantum simulation, we realize a qubit in the meta-stable fine-structure states of strontium. We demonstrate long coherence times and high-fidelity manipulation of this qubit, as well as fast initialization via coherent three-photon coupling from the ground state [3].

Our work showcases the scalability of atom arrays trapped in optical lattices and establishes the fine-structure qubit in strontium as a promising qubit platform for neutral-atom quantum computers.

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Rydberg thermometry in a Sr Optical Lattice Clock

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The relentless pursuit of higher precision in optical lattice clocks (OLC) demands ever more refined methods to mitigate environmental perturbations, with blackbody radiation (BBR) induced frequency shifts standing as a major challenge. State-of-the-art OLCs address this effect by either operating in a cryogenic environment to reduce the BBR [1], by employing comprehensive temperature monitoring and compensation techniques in room-temperature setups [2, 3] or by shielding the in-vacuum radiation inhomogeneities [4].

Atoms excited to Rydberg states have been proposed, due to their enhanced sensitivity to BBR [5], as excellent candidates for in-situ and calibration-free measurements of the BBR spectrum experienced by atoms in OLCs [6, 7]. The latest method, based on BBR-induced state transfers was recently implemented on alkali Rubidium atoms [8], demonstrating promising initial results and a first validation of this technique.

Until now, proposed methods and models have relied on Rydberg physics in alkali atoms, while OLCs are based on alkaline-earth species. In this presentation, we will first demonstrate that a method relying exclusively on BBR-induced state transfers becomes limiting when applied to divalent species due to shorter radiative lifetimes. We will introduce a new protocol tailored to divalent Rydberg atoms, leveraging their distinctive property of auto-ionization [9] through doubly excited electronic states. This method enables a continuous evaluation of the full BBR-induced lifetime and natural lifetime independently. We will develop a theoretical model based on this new framework and conclude by assessing its advantages over existing protocols, including an estimate of the achievable sensitivity and precision in our measurements. Finally, we will present the design of an experimental setup under development aimed at validating the feasibility of this approach.

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Ask what a Rydberg atom can do for your polar molecule

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Rydberg atoms and polar molecules create a divine union. Both are sought after for their precision properties for tunability and manipulation. Both are amenable to long-range interactions. Here, I will describe cooling and loading into a MOT of somewhat generic polar molecules via sympathetic collisions with laser-cooled Rydberg atoms, exploiting the naturally large Rydberg elastic cross sections. This technique does not require photon recycling [1]. The scheme exploits the interesting fact that Rydberg atoms and polar molecules in close proximity influence each other via the charge-dipole interaction. The first realization of the charge-dipole energy shift in the proximity tweezers of the Rydberg Rb atom and the NaCs molecule was made only recently [2], which I will also discuss.

Last but definitely not least, fantastic collaborations with Seth Rittenhouse, Timur Tscherebul, Rosario Gonzalez-Ferez on the theory side, and Chi-Zhang/Nick Hutzler and Alex Guttridge/Simon Cornish on the experiment side are highly acknowledged.

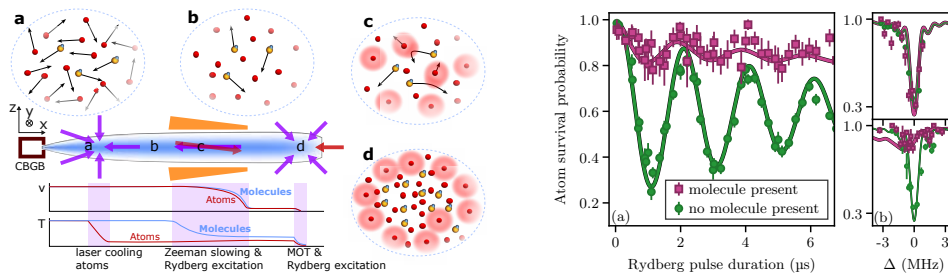


Figure 1: [left] Proposed experimental setup and sequence for sympathetic cooling of large polar molecules with Rydberg atoms [1]. [Right] Survival probability of the Rb atom as a function of the Rydberg pulse duration for $R \sim 310(40) \text{ nm}$ [2].

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Quantum simulation of molecular processes with trapped Rydberg atoms and ions

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Atoms and ions confined with electric and optical fields form the basis of many current quantum simulation and computing platforms. When excited to high-lying Rydberg states, long-ranged dipole interactions emerge which strongly couple the electronic and vibrational degrees of freedom through state-dependent forces. This vibronic coupling leads to hybridization of internal and external degrees of freedom, which we illustrate by considering few-body systems of trapped Rydberg atoms [1] and ions [2]. These platforms allow to uncover intricate dynamical and spectral signatures, among them quantum corrections to Born-Oppenheimer surfaces or structural transitions of "molecular" configurations. This highlights the potential of these systems for the quantum simulation of molecular processes in well-controlled settings at exaggerated length and time scales.

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Ultralong-Range Ytterbium Rydberg Molecules

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An ultralong-range Rydberg molecule is formed by the interaction between the electron of a highly excited Rydberg atom and a ground state atom. This leads to molecular states characterized by extreme spatial extent, large dipole moments and long lifetimes.

In this work, we present the first spectroscopic characterization of such ytterbium (Yb) Rydberg molecules in a dense and ultracold atomic gas. Using two-photon excitation, we probe the molecular binding energies and map the vibrational spectra of the 1S_0 Rydberg manifold in a wide range of principal quantum numbers. Field ionization and subsequent ion detection of the Rydberg molecules and atoms provide high-precision, background-free spectra. Using low-energy quantum scattering techniques on the observed binding energies, we extract fundamental properties of electron-Yb ground state atom scattering, including the scattering length. We find also that, unlike other two-valence electron atoms such as Sr [1], Yb has a significant p-wave resonance giving rise to deeply bound vibrational states. Additionally, we have measured the permanent electric dipole moments (PEDM) of the Rydberg molecules, which are of Debye size, indicating the mixing of nearly degenerate higher angular momentum components. A notable distinction emerges in the dependence of the PEDM on the principal quantum number n , which deviates significantly from the behavior observed in rubidium [2], where the PEDM follows a simple power law.

Accurate model wavefunctions of Yb require a multi-channel quantum defect theory (MQDT) description. Beyond measured state energies, MQDT models rely on experimental inputs such as static polarizabilities to fit channel mixing angles [3]. The sensitivity of the Rydberg molecule data to this mixing enables precise benchmarking of MQDT wavefunctions, complementing measurements of static polarizabilities and pair state potentials.

We also present our apparatus featuring a compact two-chamber design comprising a dispenser-loaded 2D MOT and a two-color 3D MOT allowing narrow-linewidth cooling of 10^7 atoms to temperatures below $10\ \mu\text{K}$ [4]. After loading into an optical trap and consecutive evaporation we reach atomic densities of $4 \times 10^{14}\ \text{cm}^{-3}$ at temperatures $T \approx 4\ \mu\text{K}$. Electrodes around the atomic cloud allow electric field background compensation, field ionization of Rydberg atoms and molecules, and their detection with a microchannel plate.

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Exploring ultracold Rydberg and molecular systems using two-species optical tweezer arrays

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Ultracold dipolar systems, like atoms excited to Rydberg states and polar molecules, hold great potential for quantum simulation and computation. Programmable arrays of optical tweezers have enabled flexible trapping of both these systems, enabling precise studies of their long-range interactions. This presentation will report our work using two-species optical tweezer arrays of Rb and Cs atoms to explore both Rydberg and molecular systems.

First, I will present experimental results demonstrating the assembly of ultralong-range Rydberg molecules from Rb and Cs atoms trapped in separate tweezers [1]. Next, I will report on experiments with individual RbCs molecules assembled in the rovibrational ground state [2]. By trapping these molecules in magic-wavelength tweezers, we achieve rotational coherence times exceeding one second, enabling the preparation of two-molecule Bell states with a fidelity of $0.976_{-0.016}^{+0.014}$ [3].

Furthermore, I will present measurements of charge-dipole interactions [4] and resonant dipole-dipole interactions between Rydberg atoms and polar molecules. These interactions open new avenues for enhancing control of molecules by enabling non-destructive detection and mediating entanglement. These results showcase how the advanced control over quantum systems achieved in optical tweezers can access new interaction regimes. These interactions, in turn, can be incorporated into future quantum science experiments using the tweezer platform.

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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.

Quantum-Non-Demolition Detection of Circular Rydberg Atoms

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Neutral atoms in optical tweezers promoted to Rydberg states are one of the most promising platforms for quantum simulation. Due to their exceptional lifetime, circular Rydberg atoms additionally offer an unprecedented potential for being trapped for timescale ranging from tenth of ms at the temperature of 4K and up to minutes when implementing spontaneous emission inhibition in cryogenic environments. We will present a state-selective and non-destructive detection method for single trapped [1, 2] circular atoms in optical tweezer. The method is based on a “dual-Rydberg” architecture combining arrays of circular atoms as computational qubits and of low angular momentum ancilla Rydberg atom for readout [3]. We also show that ancilla can be used for performing local manipulation of circular atoms.

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Towards quantum computation with Sr88 atom arrays

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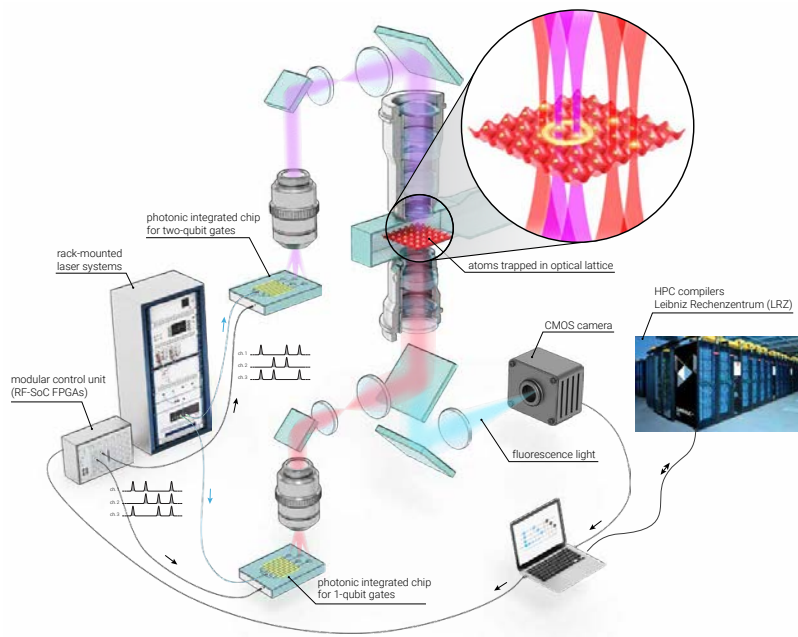
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We present our latest progress on a Sr88 atom array platform that harnesses long-range Rydberg interactions for scalable digital quantum computation.

In our system, individually trapped Sr88 atoms in arbitrary optical tweezers arrays serve as qubits featuring second-scale coherence times, state-selective detection, and a robust, non-cryogenic, vacuum-limited lifetime exceeding 1500s.

In addition, our apparatus addresses a number of technological and physical challenges in scalable quantum computing with neutral atoms, including the realization of fast, local single-qubit control via integrated photonics as well as local addressing for two-qubit gates. Furthermore, we want to overcome detrimental heating in qubit registers through carefully optimized recoil-free single-qubit operations[1].

With inherent advantages such as minimal manufacturing variations and rapid scalability, our digital quantum computing demonstrator integrates techniques from analog quantum simulation with digital gate operations, paving the way for implementing complex digital circuits and robust quantum error correction protocols while underscoring the potential of Sr88 atom arrays as a versatile technology for next-generation quantum computation.



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Self-organized criticality and prethermalization in the nitric oxide molecular ultracold plasma

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Prethermalization occurs as the quasi-equilibrium of an isolated many-body system confined to a subspace separated from thermodynamic equilibrium by an energetic or dynamic gap. Constrained relaxation in a prethermal phase can support restricted mobility in natural and model systems of high dimensionality and limited disorder. Here, we describe the signature of an enduring prethermal regime of arrested relaxation in the molecular ultracold plasma that forms following the avalanche of a state-selected Rydberg gas of nitric oxide. This robust final state, consisting of weakly associated nitric oxide ions and electrons, persists on a millisecond timescale despite accessible dissociation channels to neutral atoms. In every realization, ionization avalanches mark the initial progress to this state by a power-law size distribution that suggests an intermediate regime of self-organized critical (SOC).

For a wide range of initial conditions, this system forms an evolving phase in which a substantial density of NO^+ and electrons balances a population of Rydberg molecules. Electron collisions mix orbital angular momentum, scattering Rydberg molecules to states of very high- ℓ . Low- ℓ states rapidly predissociate, purifying this non-penetrating character, creating an extraordinary gap between the plasma states of $n \approx \ell$, with measured $n > 200$ and penetrating states of $\ell = 0, 1$ and 2 . Evolution to a statistically equilibrated state of N and O atoms cannot occur without Rydberg electron penetration, and this gap blocks relaxation for a millisecond or more.

We find that a set of coarse-grained rate laws describing electron impact ionization, recombination and neutral dissipation processes conforms with the attractor observed experimentally. The stochastic implementation of these rate processes in a percolation model captures the transition to a critical state, replicating the attractor and power-law characteristics of this system. Evolving through the critical regime, electrons that balance the NO^+ charge behave as though localized in the prethermal phase and play an ineffective role in bridging this gap. However, ℓ -mixing, driven by mm-wave Rydberg-Rydberg transitions to penetrating states or weak radiofrequency field (RF) induced electron-Rydberg collisions, bridges the angular momentum gap, causing the entire ensemble to thermalize. The molecular nitric oxide ultracold plasma offers a novel experimental and theoretical platform in which a quantitative reference to microscopic dynamics accounts for the spontaneous formation of an emergent SOC ensemble that evolves to a sub-critical prethermalized state.

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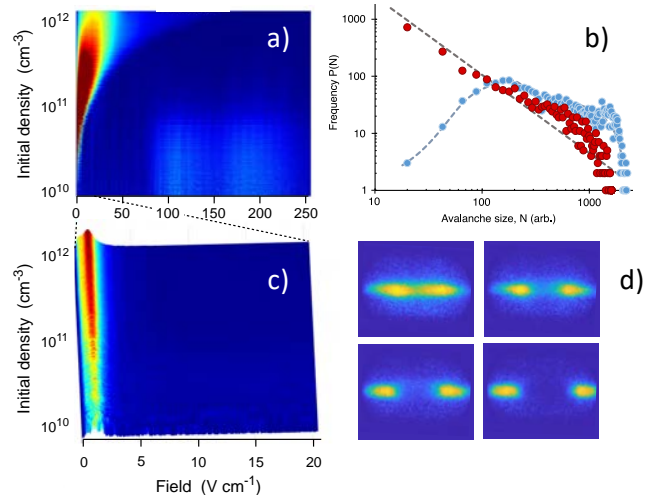


Figure 1: a) Selective field ionization spectrum of the evolving NO plasma in a power-law regime of avalanche size, b). c) Field ionization spectrum of the prethermalized state, in which no electron is bound by more than 10 cm^{-1} and the plasma bifurcates to form prethermalized volumes, d).



Friday's Abstracts

Rydberg applications: vortex beams and qudits

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Rydberg atoms are increasingly finding more and more diverse applications, from fundamental physics to sensing and computing. In this talk, we shall focus on two recent developments where we exploit Rydberg atoms to address questions in optics and computing.

In the first example, we use Rydberg atoms to image [1] the vector components of Laguerre-Gauss beams [2]. The images allow us to test and verify the accuracy of a simple vector solution of Maxwell's equations.

In the second example, we discuss the utility of Rydberg qudits. We give an example of the read out of a Rydberg qutrit as a time-bin encoded photon [3], and then go on to explain the application of single-atom Rydberg qudits to solving graph colouring problems [4].

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Controlling quantum trajectories with quantum fields

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We will discuss examples where the interplay of noise and quantum dynamics can mitigate decoherence [1, 4] and even stabilize target trajectories [2, 3, 4]. The corresponding dynamics provide an alternative, robust paradigm to existing approaches for noise mitigation and for quantum annealing.

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Rotating dipolar supersolids

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Supersolids are exotic states of matter that spontaneously break two symmetries: gauge invariance through the phase-locking of the wavefunction, and translational symmetry owing to the emergence of a crystalline structure. First predicted in solid helium, they have recently been observed in ultracold atoms, with particular success coming from dipolar atoms [1, 2, 3, 4]. The crystalline structure is naturally observable as a modulation of the integrated in situ density profile. Phase coherence has instead been probed by studying the self-interference pattern of an expanding supersolid [1, 2, 3] and the emergence of Goldstone modes [5]. Yet, a defining hallmark of superfluidity—quantized vortices—had remained elusive. Here, we report on the theoretical study and experimental observation of vortices in a dipolar supersolid of dysprosium [6]. When rotated, our supersolid shows a mixture of rigid-body and irrotational behavior, highlighting a fundamental difference between modulated and unmodulated superfluids. Additionally, we observe that vortices nucleated in the rotating supersolid state trigger a synchronization of the crystal’s motion to the external driving frequency [7]. By analyzing this process, we determine the energetic critical frequency for vortex nucleation and gain insight into the interplay between superfluidity and crystallinity in supersolids. Our observations open the way to study the peculiar properties of vortices in supersolids: the reduced angular momentum [8, 9], the influence of the crystal structure on the vortex dynamics [10, 11, 12] and further applications to the study of other systems with multiple spontaneously broken symmetries, such as neutron stars [10].

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Realization of topological Thouless pumping in a synthetic Rydberg dimension

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The simulation of synthetic dimensions by manipulating internal states of atoms and molecules has provided the opportunity to investigate regimes outside those of more traditional quantum many-body platforms. Highly excited Rydberg states of atoms are a particularly promising platform to engineer Hamiltonians in such synthetic dimensions due to their large number of addressable states and the readily available technologies for manipulating their couplings and for detecting them [1].

In this talk, I will demonstrate the realization of topological quantum pumping in synthetic dimensions by engineering a one-dimensional Rice-Mele chain from the Rydberg states of cesium atoms and manipulating their couplings in a time-dependent fashion through radio-frequency fields. To this end, the Thouless protocols for topological pumping is implemented. We investigated the efficiency for pumping an effective quantum particle as a function of the period of pumping and other parameters. Optimal pumping efficiencies of up to 90% are demonstrated when the pump is operated in the topological Thouless regime, even when the pumping is accompanied by the wave-packet spread that arises from the energy dispersion of the particle along the synthetic dimension [2].

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Atomic Ensembles with Rydberg Excitations

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Laser-cooled and trapped ensembles of neutral atoms have utility in the long-term goal of quantum networks - as atomic memories, efficient sources of individual photons, quantum sensors, and matter-photon transducers. Much of the utility comes essentially for free - excitations are shared among the atoms in a quantum superposition that encodes the propagation phase. This spin wave can then be read out with high directionality as a result of the inherent phased-array nature of the superposition. Using Rydberg excitation and the Rydberg blockade effect can guarantee single-photon emission with high purity. As an example, we demonstrated a single-photon source with a second-order correlation function of $g^{(2)} = 5 \times 10^{-4}$ using a single blockaded Rydberg excitation to $139S_{1/2}$ in ^{87}Rb [1].

To further enhance the utility of such systems and move beyond the native Van der Waals interaction, one can introduce microwave dressing with microwave coupling between opposite-parity Rydberg levels to modify interactions. The extremely large matrix elements coupling $nS \rightarrow nP$ allows the creation of large Rabi frequencies with modest microwave powers. Tuning the strength and angular dependence of the dipole-dipole interaction, as well as its scaling with atom separation, can enhance and expand the capabilities of interacting Rydberg systems.

We have implemented microwave dressing in our atomic ensemble system. Our vacuum system was not designed for microwaves, as it is a metal chamber with multiple DC electrodes, and only DC electrical feedthroughs. Nonetheless, by applying three microwave sources with amplitude and phase control through the DC feedthroughs, we can dress the atoms with complete control over the microwave polarization. Using microwave electrometry via EIT spectroscopy, we develop a "chamber matrix" that transforms microwave inputs into polarization states at the atoms. Using two-photon microwave transitions to D states, we can define the polarization off-resonance as well, necessary for certain dressing proposals.

By varying the cloud length relative to the blockade radius and measuring the statistics of the light retrieved from the ensemble, we demonstrate a clear enhancement of the interaction strength due to microwave dressing. These results are successfully captured by a theoretical model that accounts for excitation dynamics, atomic density distribution, and phase-matched retrieval efficiency. [2].

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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 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 priori 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.

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Rydberg-atom interferometry and electrometry for tests of positronium gravity

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Electric Rydberg-atom interferometry [1], an electric analogue of Stern-Gerlach interferometry [2, 3], is well suited to the measurement of acceleration due to gravity (g), and testing the weak equivalence principle (WEP), with purely leptonic atoms such as positronium (Ps) [4]. With this in mind, we have recently designed and performed a numerical analysis of the operation of a full-loop electric Rydberg-atom interferometer that could allow a measurement of g for Ps to a precision of 10%. To achieve the control and characterisation of the electric fields required in this apparatus, Rydberg atoms in Schrödinger cat states with oppositely orientated static electric dipole moments can be used as quantum sensors. In this contribution, we will describe the operation of the Ps Rydberg-atom interferometer, and the experimental implementation of a broad-band RF sensor using helium atoms in these Schrödinger cat states. We will also describe progress towards the implementation of a prototype full-loop electric Rydberg-atom interferometer with beams of helium atoms.

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Towards a Portable Two-Photon Cesium Optical Clock

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Optical clocks have the prospect to greatly improve the precision and portability of timekeeping devices. With this goal in mind, we are developing a clock stabilized to a two-photon optical transition in cesium (Cs). Two-photon transitions can be insensitive to first-order Doppler shifts and are thus good candidates for portable clocks. Cs atoms in a hot vapor cell are driven on the 6S to 7D transition by a retroreflected laser stabilized to the atomic fluorescence peak. Systematic errors and fluorescence detection requirements for this Cs transition are favorable compared to similar rubidium-based vapor clocks. We directly compare the optical reference to a GPS steered microwave clock via an optical frequency comb to extract an upper bound on clock performance. We also exploit photonic integrated circuit technology to develop tantalum pentoxide microresonators that can produce Kerr soliton frequency combs. In the future, the stability of our optical reference will be transferred through these chip-based combs to the microwave domain allowing for direct interfacing with conventional electronics and devices. We also report on preparing the clock for operation of these clocks in GPS stations located in the Canadian north.

This work has been supported by DRDC Canada.



Poster's Abstracts

Information-theoretic quantifiers of electron correlation and confinement

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In this work, we study the helium atom confined in a spherical impenetrable cavity [1] by considering a diversity of informational measures [2]. The Ritz variational method is employed to obtain the energies and wave functions of the confined helium atom [3] as a function of the cavity radius r_0 . As trial wave functions we use one uncorrelated function and five explicitly correlated basis sets in Hylleraas coordinates with different levels of electronic correlation. We computed [2] the Shannon entropy, Fisher information, Kullback–Leibler entropy, Tsallis entropy, disequilibrium and Fisher–Shannon complexity, as a function of r_0 .

Most information measures reveal differences between the values obtained from wave functions with and without correlation; then, we may consider those differences as a measure of correlation, which varies with r_0 . As expected [4] these entropic functionals are less sensitive to electron correlation in the strong confinement regime ($r_0 < 1$ a.u.).

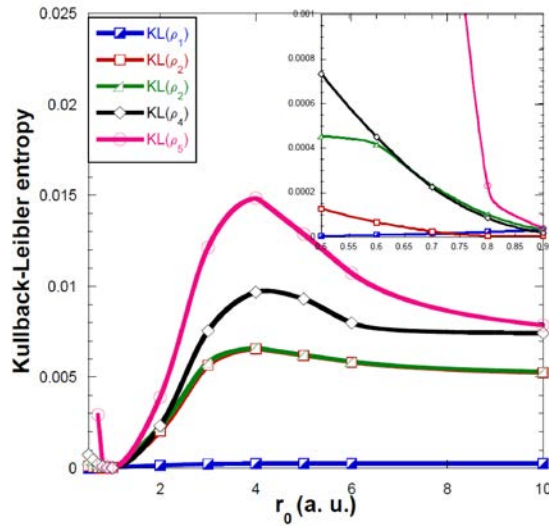


Figure 1: Kullback-Leibler entropy, as a function of the confinement radius r_0 , between the uncorrelated wavefunction and each one from a set of wavefunctions with increasing degree of correlation (from Ref. [2]).

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Stark Measurements in Nitric Oxide using a Three Photon Excitation Scheme for a Trace Gas Sensor

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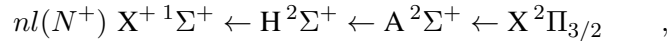
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At the beginning of the 1990s it was known, that nitric oxide (NO) plays an important role as a signaling molecule in the mammalian system, and a change of its concentration in the exhaled breath may indicate certain diseases . We showed in a proof-of-concept experiment the operation of a NO trace-gas sensor at ambient pressure at a concentration of 10 ppb.

Our detection principle is based on the electronic amplification of a current generated by free charges resulting from collisions of NO molecules in a Rydberg state with background particles. For the excitation we use continuous-wave (cw) laser systems for the transitions



which are at about 226 nm, 540 nm and 835 nm, respectively.

We investigated the collisional shift and line broadening of Rydberg states in nitric oxide (NO) with increasing density of a background gas at room temperature [1]. As a background gas, we either use NO itself or nitrogen (N₂) and identify pressures for an optimal operation of our sensor.

We measured Stark Maps to investigate optimized electric fields for our NO detection and extracted improved values for the quantum defects of the rotational ground state ($N^+ = 0$). In these measurements, we saw unshifted lines not explained by theory [2].

Besides these non-shifting lines, we also observed very weak lines, that exhibit a Stark-Effect. This poster focuses on these unexplained lines.

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The iSWAP gate with polar molecules: Robustness criteria for entangling operations

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Ultracold polar molecules trapped in optical lattices or tweezer arrays are an emerging platform for quantum information processing and quantum simulation, thanks to their rich internal structure and long-range dipolar interactions. Recent experimental breakthroughs have enabled precise control over individual molecules, paving the way for implementing two-qubit quantum gates, based on the iSWAP gate. A key challenge is however the sensitivity to variations of the dipole-dipole interaction strength – stemming from motion of the molecules and uncertainty on the precise positioning of external confining potentials – that limits current gate fidelities. To address this, we develop a quantum optimal control framework, based on a perturbative approach, to design gates that are robust with respect to quasi-static deviations of either system Hamiltonian parameters, external control parameters, or both, and provide criteria to evaluate a priori whether a gate can be made robust for a given control Hamiltonian. By applying these criteria to exchange-coupled qubits, as polar molecules, we demonstrate that robustness cannot be achieved with global controls only, but can be attained by breaking the exchange symmetry through local controls, such as a local detuning. We determine the robust time-optimal solution for realizing an iSWAP gate, show that the control pulses can be designed to be smooth functions, and achieve theoretical gate fidelities compatible with error correction using reasonable experimental parameters. Additionally, we show that certain entangled state preparations, such as Bell states, can be made robust even with global controls only.

For more information, see Ref. [1, 2, 3]

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Tuning a strong single-photon transition between low- ℓ Ryberg states into resonance with a superconducting co-planar waveguide resonator using AC Stark shifts

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Hybrid quantum interfaces between Rydberg atoms and superconducting microwave circuits offer opportunities for networking neutral atom and superconducting quantum processors. Up to now, work at these interfaces has centred around managing effects of stray electric fields caused by adsorbates and charge buildup on the cryogenically cooled superconducting chip surfaces. These efforts led to the first demonstrations of coherent coupling between Rydberg atoms and superconducting co-planar waveguide (CPW) resonators [1-4]. However, so far, this coupling has relied on the use of either two-photon transitions in electric fields close to zero, or weak single-photon transitions in strong DC offset electric fields.

Here, we demonstrate the coupling of a strong single-photon electric dipole transition between the low- ℓ triplet $1s50s\ ^3S_1$ and $1s50p\ ^3P_J$ Rydberg states in helium, to the 11.752 GHz second harmonic mode of a quarter-wave niobium nitride CPW resonator, in near-zero DC electric field. This represents the first demonstration of coupling the microwave field in a superconducting CPW resonator to a single-photon transition between Rydberg states with a large electric dipole transition moment ($\sim 1500\ ea_0$). To achieve this, a microwave dressing field, detuned from the $1s50p\ ^3P_J - 1s50d\ ^3D_J$ transition, was used to tune the $1s50s\ ^3S_1 - 1s50p\ ^3P_J$ transition into resonance with the resonator using the AC Stark effect. This approach allowed the microwave power in the resonator to be reduced by more than 3 orders of magnitude compared to previous work, moving this hybrid quantum system closer to the single-photon strong-coupling regime.

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Impact of nuclear elastic p-p cross section on Monte Carlo proton transport simulation

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-Introduction-

Monte Carlo simulations are widely used in proton therapy to analyse the interaction of protons with matter. This type of codes takes into account both the electromagnetic and nuclear part of the proton interaction. In this work, our goal is to analyse the implementation of the nuclear part in the simulations code PENH [2, 3], specifically, the channel related to the nuclear elastic p-p interactions. To study the nuclear elastic p-p interactions, an experiment where the importance of the nuclear elastic p-p contribution is more relevant than the electromagnetic one has been considered.

-Materials and Methods-

We perform a simulation, using PENH, to reproduce the experimental results obtained in [1]. We compare the Monte Carlo and the experimental results, in order to understand the differences between them, and what is the physics under this results.

-Results-

Some relevant differences are obtained when comparing off-axis doses with the results obtained with PENH. Changing the parametrization used to model the differential cross section of nuclear elastic p-p interactions, significant changes have been found in the results obtained in the simulation. This point out that the differences found are due to the model used to implement the nuclear elastic p-p contribution. A new parametrization for the differential cross section of this process [4] is used to implement this kind of interaction, obtaining a better agreement between the Monte Carlo and experimental results.

-Conclusions-

We have checked the p-p nuclear elastic contribution, finding a problem in its implementation in PENH. This problem has been solved with a new parametrization of the cross section used to described this kind of interaction. With this change, a better agreement between the Monte Carlo and experimental results is obtained.

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Self-organized criticality and prethermalization in the nitric oxide molecular ultracold plasma

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Prethermalization occurs as the quasi-equilibrium of an isolated many-body system confined to a subspace separated from thermodynamic equilibrium by an energetic or dynamic gap. Constrained relaxation in a prethermal phase can support restricted mobility in natural and model systems of high dimensionality and limited disorder. Here, we describe the signature of an enduring prethermal regime of arrested relaxation in the molecular ultracold plasma that forms following the avalanche of a state-selected Rydberg gas of nitric oxide. This robust final state, consisting of weakly associated nitric oxide ions and electrons, persists on a millisecond timescale despite accessible dissociation channels to neutral atoms. In every realization, ionization avalanches mark the initial progress to this state by a power-law size distribution that suggests an intermediate regime of self-organized critical (SOC).

For a wide range of initial conditions, this system forms an evolving phase in which a substantial density of NO^+ and electrons balances a population of Rydberg molecules. Electron collisions mix orbital angular momentum, scattering Rydberg molecules to states of very high- ℓ . Low- ℓ states rapidly predissociate, purifying this non-penetrating character, creating an extraordinary gap between the plasma states of $n \approx \ell$, with measured $n > 200$ and penetrating states of $\ell = 0, 1$ and 2 . Evolution to a statistically equilibrated state of N and O atoms cannot occur without Rydberg electron penetration, and this gap blocks relaxation for a millisecond or more.

We find that a set of coarse-grained rate laws describing electron impact ionization, recombination and neutral dissipation processes conforms with the attractor observed experimentally. The stochastic implementation of these rate processes in a percolation model captures the transition to a critical state, replicating the attractor and power-law characteristics of this system. Evolving through the critical regime, electrons that balance the NO^+ charge behave as though localized in the prethermal phase and play an ineffective role in bridging this gap. However, ℓ -mixing, driven by mm-wave Rydberg-Rydberg transitions to penetrating states or weak radiofrequency field (RF) induced electron-Rydberg collisions, bridges the angular momentum gap, causing the entire ensemble to thermalize. The molecular nitric oxide ultracold plasma offers a novel experimental and theoretical platform in which a quantitative reference to microscopic dynamics accounts for the spontaneous formation of an emergent SOC ensemble that evolves to a sub-critical prethermalized state.

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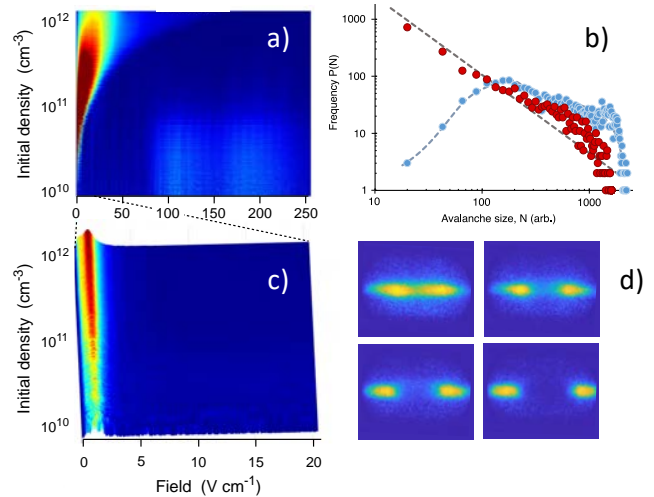


Figure 1: a) Selective field ionization spectrum of the evolving NO plasma in a power-law regime of avalanche size, b). c) Field ionization spectrum of the prethermalized state, in which no electron is bound by more than 10 cm^{-1} and the plasma bifurcates to form prethermalized volumes, d).

Construction and Characterization of a Ca Magneto-Optical Trap for Rydberg Physics

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Ultracold gases of divalent atoms excited to high Rydberg states are an exciting tool to explore subjects from fundamental Rydberg physics to quantum simulation [1]. While calcium has received little attention compared to other divalent species such as strontium or ytterbium, its unique features, including low autoionization rates or the smallest electronic affinity of all atomic species, are expected to open up new possibilities to control, manipulate and study Rydberg gases. We will report on the development of an experimental setup for ultracold calcium Rydberg atoms.

Our experimental setup features a custom-made oven combined to a 3D-printed permanent-magnet Zeeman slower, for first stage cooling of calcium atomic beam. Atoms exiting the Zeeman slower at velocities near 30 m/s are then trapped in a magneto-optical trap whose magnetic-field gradient is generated with a pair of home-built coils than can withstand large currents (> 220 A). This approach allows us to prepare a trapped ensemble of Ca atoms at a temperature of a few mK. We then employ a resonant three-photon scheme to excite ground-state atoms to $4snp\ ^1P$ and $4snf\ ^1F$ Rydberg states. The measurement of the detailed properties of our calcium magneto-optical trap, together with the modelling and characterization of the Rydberg excitation, is currently under way and will be reported in our communication. With the present setup, we will be in a position to investigate the direct cooling of Rydberg atoms with an isolated core transition [2] or high lying doubly excited "planetary" states of the Ca atom.

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Sum Frequency Bandwidth Compression for Picosecond Rydberg Excitation

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Rydberg atoms play a key role in quantum technologies using neutral atoms, as their gigantic orbital allows strong interactions. In our previous work, we have excited Rubidium atoms to a single Rydberg states as fast as 10 picoseconds, limited by the energy splitting between two consecutive Rydberg levels of ≈ 100 GHz (Fig. 1(b)) [1]. The required spectral resolution was obtained by spectrally shaping (cutting) the laser pulse bandwidth from 800 GHz to 30 GHz, causing 96% of pulse energy loss. In this study, we implement the technique of Sum Frequency Bandwidth Compression (SFBC) in our laser system by using Chirped Bragg Grating (CBG) [2], allowing to directly generate a 480 nm pulse with a bandwidth of 21 GHz by converting a 780 nm and 1250 nm pulses, with respectively a bandwidth of 700 GHz and 500 GHz (Fig. 1(a)). Thanks to the direct generation of narrow-band sum-frequency pulse without any following spectral shaping, the new setup provides a pulse energy of 15 μ J, which is about 10 times larger than in [1]. With this new 480 nm pulse, we successfully demonstrate single state Rydberg excitation of Rubidium atoms trapped in optical tweezers, by performing a Rydberg spectroscopy. We can resolve nD states from $n = 33$ to $n = 53$ (Fig. 1(c)), confirming a state-selective excitation. This new excitation pulse will enable us to scale-up Rydberg atomic ensemble, as well as to perform more robust Rydberg excitation schemes toward high-fidelity gate operations.

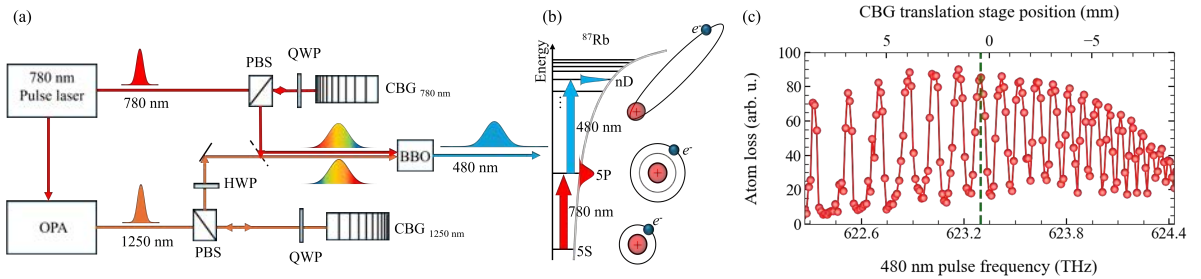


Figure 1: (a) Sum frequency bandwidth compression setup. (b) Electronic structure of Rubidium 87 atom (not at scale), combined with the excitation procedure [1]. (c) Rydberg spectroscopy. The green dashed line corresponds to $n = 39$.

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Electronic structure calculations for electron driven reactivity of PH^+

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Measurements of trace gases in the atmosphere of Venus indicate the presence of phosphine (PH_3) and other phosphorus hydrides [1]. Thus the chemistry of PH_3 is assumed to play an important role in the atmosphere of Venus. The simplest among phosphorus-hydrides is the PH and its cation, PH^+ .

The electron impact recombination of molecular cations is in the heart of the molecular reactivity in cold ionised media [2]. To study the dissociative recombination (DR) of PH^+ we need to calculate the potential energy curves (PEC) followed by nuclear dynamical calculations. For a consistent dynamical model all PECs and couplings have to be calculated at the same level of theory. We have performed the calculation of the PECs of PH^+ with the multireference configuration interaction (MRCI) method including the $2,4\Sigma^-$, $2,4\Sigma^+$, $2,4\Pi$, $2,4\Delta$ - Fig. 1 - states followed by the determination of the PECs of PH with the same approach for $1,3\Sigma^-$, $1,3\Sigma^+$, $1,3\Pi$, $1,3\Delta$ states with MOLPRO [3] and R-matrix method [4]. These PECs provide the possible reaction paths for DR, either through autoionizing doubly excited valence states or mono-excited Rydberg states.

The calculated cross sections and rate coefficients will be useful in the interpretation of the observations of ESA EnVision mission (2031).

The work is supported by the EKÖP-24-3-II-DE-347 University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

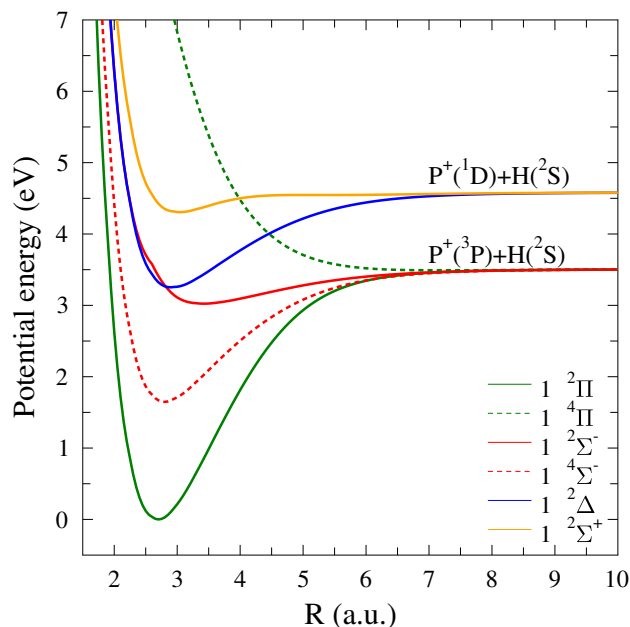


Figure 1: The first, preliminary potential energy curves of the PH^+ molecular cation as the function of the internuclear distance.

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Photoionization of Rydberg atoms due to the presence of high-intense trapping beams

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Rydberg atoms are one of the most promising candidates for quantum technologies. One can exploit the Rydberg blockade effect to create quantum *CNOT* gates. We explore Rydberg atoms in the presence of optical nano-fibres (ONF) as they provide a large interaction region with high-intensity electrical fields without demanding high laser power. We cool down the Rb^{87} atoms in the MOT configuration, which is overlapped with the ONF. From the MOT we can excite atoms to different Rydberg states via a 2-photon process, where the first photon (780 nm) is from the cooling beams, and the second photon (480 nm) is guided through the ONF [1]. When atoms undergo Rydberg excitation, they are lost from the MOT, resulting in the reduction of fluorescence, giving us an indirect measurement of the excitation rate. We have achieved Rydberg excitations from the MOT for principal quantum number of $n = 24$ up to $n = 68$ [2].

To further explore the mechanism of the Rydberg blockade and interaction with a dielectric fibre surface, we have realized the two-colour dipole trapping of neutral atoms via the ONF-based evanescent field. We have optimized the trap using a machine-learning algorithm, which helped us to reach the number of around 300 atoms trapped.

Before starting the exploration of Rydberg excitation from the dipole trap, we expected fibre-surface interactions to influence the Rydberg atoms. We noticed the effect of the presence of trapping beams going through the ONF on the Rydberg spectra. In the trapping beams configuration during Rydberg excitation, we can observe the spectrum broadening, which we believe may be connected to the photoionization of the Rb atoms, resulting in the deposition of charges on the ONF surface.

In this work, we explore the nature of this effect, applying different fields at different timescales. We also investigate methods to decrease the influence of this effect on the Rydberg atoms spectrum.

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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.

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 [1]. 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 [2, 3]. 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. In particular, for a bound state between two Rydberg atoms and one ion, we predict a rich interaction potential that comprises the interaction between induced dipoles, ion-Rydberg atom interactions, and the Rydberg blockade effect.

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Investigating the quadrupole moment of the $41D_{5/2} \rightarrow 39G_{9/2}$ transition using EIT

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In this work, we propose a method to measure the electric quadrupole moment using electromagnetically induced transparency (EIT) in a four-level atomic system arranged in a ladder configuration. The probe beam, at 780 nm, couples the ground state $5S_{1/2}$ to an intermediate state $5P_{3/2}$. The coupling beam, at 480 nm, couples the intermediate state $5P_{3/2}$ to the Rydberg state $41D_{5/2}$. Finally, the $39G_{9/2}$ state is coupled by a microwave (MW) field at 71206.4 MHz. We have measured the EIT peak splitting for the quadrupole transition as a function of MW power. To calibrate the field, we have used the EIT spectrum in a nearby electric dipole transition $41D_{5/2} \rightarrow 43P_{3/2}$. Currently, we are developing a theoretical model to estimate the quadrupole moment of the transition based on experimental data.

This work is supported by grants 2019/10971-0 and 2021/06371-7, São Paulo Research Foundation (FAPESP), and CNPq (305257/2022-6). It was also supported by Army Research Office - Grant Number W911NF-21-10211.

Reciprocal Floquet Thermalization in one dimensional Rydberg atom array

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We control and manipulate Floquet thermalization in a disorder-free one-dimensional chain of strongly interacting Rydberg atoms. Central to the controllability is an experimentally feasible Floquet driven protocol, where the Rydberg excitation laser is switched on and off periodically. Through exact diagonalization of finite chains, signatures of the thermalization are determined from level statistics and stroboscopic dynamics. Focusing on the moderate frequency driving, we show that the thermalization occurs continuously when laser detuning Δ comparable to the nearest-neighbor interaction V_0 . When the detuning is larger, however, the thermalization emerges sequentially when $\Delta + V_0 \approx K\Omega$. Sequential thermalization peaks are separated by integrable regions where formation of edge modes prevents thermalization. We demonstrate that even simple pure states can thermalize, and hence allow to probe the sequential thermalization. Our study opens a route to probe and control integrability and thermalization in the Floquet driven Rydberg atom arrays.

Generation of motional squeezed states for neutral atoms in optical tweezers

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Optical tweezers have been proven to be a powerful tool to control the motion of single neutral atoms. Once cooled down to the motional ground state, the remaining uncertainties on the atomic motion are ultimately set by quantum fluctuations. We demonstrate here the squeezing of the motional state, to decrease further the position statistical spreading, at the expense of increasing the momentum one.

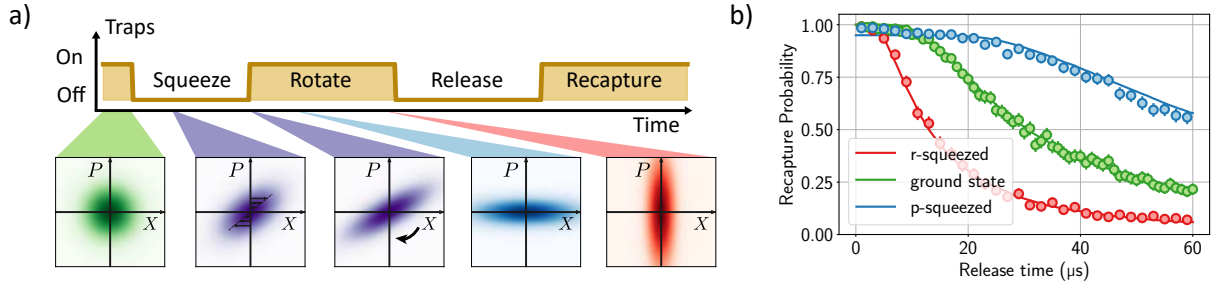


Figure 1: Squeezing generation and measurement. a) Experimental sequence, with sketches of the probability density in the X - P plane through time. b) Measured recapture probabilities for different motional states.

Our protocol, inspired by [1], to prepare and measure the squeezed state, is displayed in Figure 1a. It relies on the release of the atoms from the trap, shearing the probability distribution in the X - P plane. Then, switching on the trap again, we obtain a rotating elongated distribution, alternating between momentum- and position-squeezed states. Finally we perform a release and recapture experiment to probe the momentum distribution spreading (Figure 1b).

We report the generation of 6 dB-squeezed states. We analyze the squeezing performance limits due to the trap anisotropy and shape inhomogeneities, and how we compensate for it with precise holographic techniques [2]. We also comment the inherent limit induced by the optical tweezer anharmonicity. Our work opens perspectives for the exploration of short distance Rydberg-Rydberg interaction [3], where the effect of position noise would be detrimental.

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Quantification of the closeness of quantum states for central-type systems by quantum similarity measures

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The similarity of quantum-mechanical solutions for central potentials is analytically determined and numerically explored for arbitrary dimensionalities. The study here provided focuses on hydrogenic systems and the harmonic oscillator, in respective non-relativistic frameworks. A diversity of analytical expressions for the quantum similarity measure (QSM) and index (QSI) are provided. Relevant conclusions are derived from the analyses grounded on state quantum numbers, space dimensionality and on the role played by the main characteristic parameters of these systems, namely the nuclear charge in the hydrogenic case, and the angular frequency for the oscillator. For this purpose, a statistical analysis of the QSI values has been performed for a large number both of states and combinations of them in each system. Considering the factorization of QSI into a radial and an angular part, particular attention is paid to the individual contribution of each part in both systems.

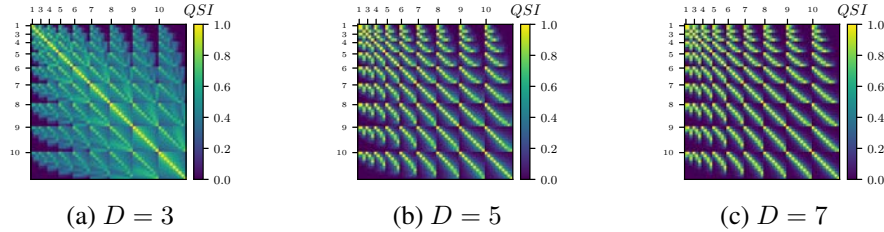


Figure 1: $QSI(R_1^2, R_2^2)$ of the hydrogenic radial part for different dimensions. Axes ticks correspond to the principal quantum number n , and intervals to the respective ranges $l = 0, \dots, n - 1$.

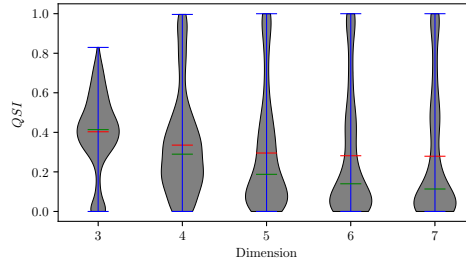


Figure 2: Violin plot of $QSI(R_1^2, R_2^2)$ for radial parts of hydrogenic systems for $D = \{3, 4, 5, 6, 7\}$ (median in green, mean in red).

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The Neutral-Atom Quantum Computer Community in Japan

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The Moonshot Research and Development Program (2020-2030) is a bold initiative by the Japanese Cabinet Office to drive innovation and address societal challenges [1]. The Goal #6 of this program is “Fault-tolerant quantum computing”, and our team at the Institute for Molecular Science has established a project gathering experts across leading institutes in Japan collaborating to develop “neutral-atom quantum computers” based on arrays of atoms trapped in optical tweezers and excited to gigantic Rydberg orbitals. This poster will introduce this effort and its participants.

In parallel, a new Japan-Germany binational project (ASPIRE, 2025-2030) has been created to accelerate development by connecting leading experts and promoting young researcher exchange to share best practices and inspire innovation [2]. As the community manager within the ASPIRE project, I am responsible for facilitating these exchanges, fostering collaboration, and ensuring the successful integration of young scientists into the growing neutral-atom quantum computing community.

The initiative that I lead, as a community manager, includes workshops, scientific retreats, student internships, and public engagement. So far, we have hosted more than 30 visiting students and researchers to foster collaboration and expand the quantum community in Japan.

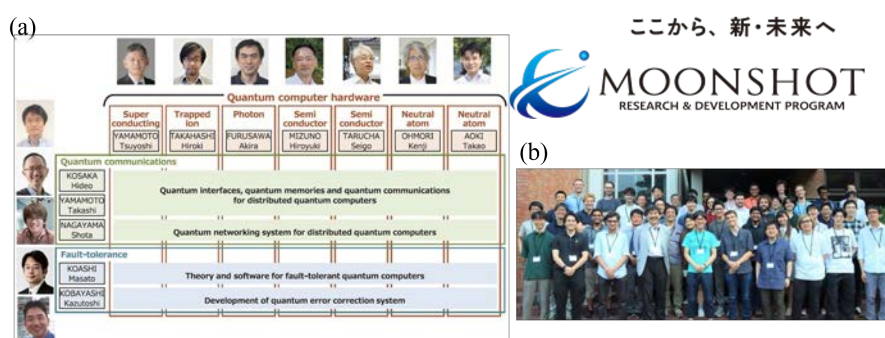


Figure 1: (a) Moonshot goal 6 PI's structure. (b) “Atoms in optical tweezers” Workshop members.

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A Rydberg tweezer array platform for simulating lattice gauge theories

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Gauge theories are fundamental in physics, spanning from the description of the interactions between particles in high-energy physics to effective low-energy models in condensed matter systems. Lattice gauge theory, a discretized version of the theory in hand, reduces the number of degrees of freedom to a finite set, making it practical for computer and quantum simulations. Computer simulations have so far successfully explored gauge theory dynamics for small system sizes or equilibrium properties in larger systems. Quantum simulation holds promise for studying the dynamical behavior of lattice gauge theories over long timescales and extending investigations to higher-dimensional systems. However, achieving simulations beyond one dimension requires engineering multibody interactions, a challenge that remains open.

Rydberg atom arrays in optical tweezers present a compelling platform for such simulations, as their tunable interactions naturally map onto spin-type Hamiltonians, making them well-suited for realizing lattice gauge theories. Our goal is to develop a highly configurable Rydberg tweezer experiment using ^{88}Sr atoms to implement the Rokhsar-Kivelson (RK) Hamiltonian, which describes a two-dimensional $U(1)$ lattice gauge theory. Building on [1], we employ a dual Ising spin formulation, where multi-body plaquette interactions—analogueous to magnetic interactions in electromagnetism—are mapped onto spin-flip operators subject to Rydberg blockade conditions.

Here, we present the latest progress in constructing our experimental platform. We detail the laser cooling scheme required for preparing and trapping individual atoms in optical tweezers, along with our initial tweezer test setup. Additionally, we describe the implementation of electromagnetic field control via a system of coils and electrodes, as well as the Rydberg excitation scheme.

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Approximate symmetries of long-range Rydberg molecules including spin effects

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An operator that generates an approximate symmetry of long-range Rydberg molecules (LRRMs) formed by two alkali atoms, one in a Rydberg state and the other in the ground state, is identified. This is first done by evaluating the natural orbitals associated with a variational calculation of the binding wave function within the Born-Oppenheimer description of the molecule including s and p Fermi pseudopotential and the hyperfine structure energy terms. The resulting orbitals with the highest occupation number are shown to be identical to those obtained by a perturbative model for high angular momentum—trilobite and butterfly—LRRMs. Whenever the slight dependence of the quantum defects of the Rydberg electron on its total momentum \mathbf{j} can be neglected, the symmetry operator of the high angular momentum LRRMs orbitals is identified as the sum of the spin of the Rydberg electron \mathbf{s}_1 , spin of the valence electron \mathbf{s}_2 and the nuclear spin \mathbf{i} , of the ground-state atom, $\mathbf{N} = \mathbf{s}_1 + \mathbf{s}_2 + \mathbf{i}$. The spin orbitals that diagonalize \mathbf{N} define compact basis sets for the description of LRRMs. The expected consequences of this approximate spin-symmetry on the spectra of LRRMs are briefly described.

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Ionization threshold energy measurement of the Rb_2 molecule using molecular Rydberg states

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In this work, we have experimentally investigated the bottom of the fundamental ionization potential ($X^2\Sigma_g^+$) for Rb_2^+ . This was done using the resonantly enhanced 2-photon ionization (RE2PI) technique applied to a supersonic beam of Rb_2 molecules. Two pulsed lasers were used; the first one excites the transition $X^1\Sigma_g^+(v_X = 0) \rightarrow B^1\Pi_u(v_B = 2)$, while the second one is swept around the bottom of the fundamental ionization potential. Afterward, a high voltage pulsed field ionization (PFI) is applied to the sample, and the ions are pushed to a channeltron and counted. By analyzing the ionization spectra of the Rydberg molecular states for several electric field amplitudes, we can identify the fundamental ion state $X^2\Sigma_g^+(v_x^+ = 0)$ of the Rb_2 molecule. Our measurement of the ionization energy is $E_i = 31498(1) \text{ cm}^{-1}$ (with a dissociation energy of $D_0 = 6158(1) \text{ cm}^{-1}$), which is 150 cm^{-1} higher than reported by Bellos et al.[1] and is in better agreement with recent theoretical models [2, 3].

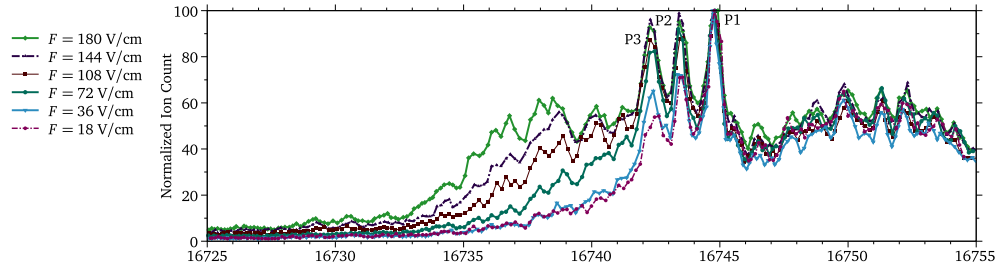


Figure 1: Normalized ionization spectra as a function of the second photon frequency for several PFI intensities ($F = 180, 144, 108, 72, 36,$ and 18 V/cm)

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Acknowledgments

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Complex Potential Energy Surfaces for Penning Ionization Through Complex Basis Functions

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Penning ionization (PI) is a phenomenon where a neutral atom or molecule (say B) is ionized upon approaching another neutral atom in its internally excited metastable state (say A^{*})—with a sufficiently long lifetime that does not decay through spontaneous emission[1]. It is commonly represented as:



PI occurs when the excitation energy of A^{*} is higher than the ionization potential of B. Energetically, PI is highly exothermic, allowing such collisions to occur even at very low collision energies, within the cold-chemistry regime[2]. During the interaction, an auto-ionizing complex (A^{*}-B) forms, which is categorized as a Feshbach resonance—a subset of electronic resonances[3]. To accurately model these resonances, non-Hermitian quantum chemical methods have been found to be particularly effective[4, 5]. Among the various available approaches, the complex basis functions (CBFs) method is known for its general applicability to molecular resonances. This technique yields complex potential energy surfaces (V) as functions of the inter-atomic distance (R):

$$V(R) = V_*(R) - i\frac{\Gamma(R)}{2}, \quad (2)$$

where the real part $V_*(R)$ describes the relative dynamics, and the imaginary part $\Gamma(R)$ characterizes the ionization probability and is directly related to the lifetime of the complex ($\tau = 1/\Gamma$). Here, we investigated He^{*}(³S) + Ar, He^{*}(³S) + H, and Ne^{*}(³P_{0,2}) + Ar chemical systems using the equation-of-motion coupled-cluster method with single and double excitations (EOM-CCSD) combined with CBFs. We demonstrate that the CBF approach provides a robust framework for modeling PI, despite the considerable computational cost involved. The obtained results are compared with the available experimental data.

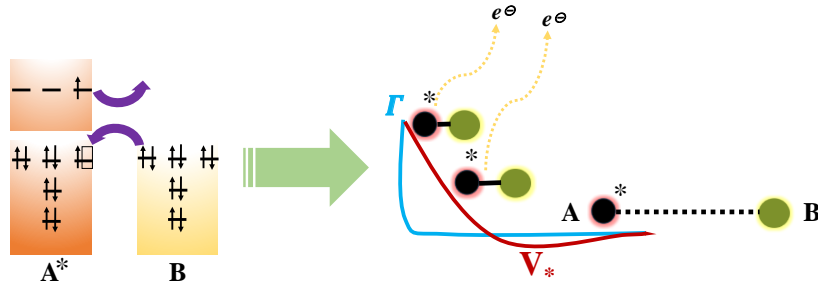


Figure 1: Penning ionization, graphical abstract.

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High-resolution spectroscopy and multichannel quantum-defect-theory analysis of high atomic Rydberg states with open-shell ion cores.

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Highly excited Rydberg states of atoms with open-shell ion cores are interesting because of their potential in quantum-information-processing, quantum sensing applications, and the determination of physical constants and atomic properties. High-resolution spectroscopy is essential for characterizing the electronic structure and the fundamental properties of these atomic systems. These properties include, but are not limited to the ionization energies, the hyperfine structure, and the corresponding isotopic shifts.

High-resolution spectra of high np and nf Rydberg series of Kr and Xe were measured by single-photon excitation from the $Rg (np)^5((n+1)s)^1 \ ^3P_2$ metastable state to study bound Rydberg states located below the $Rg^+(np)^5 \ ^2P_{3/2}$ ionization threshold, and autoionizing Rydberg states located between the $Rg^+(np)^5 \ ^2P_{3/2}$ and $Rg^+(np)^5 \ ^2P_{1/2}$ ionization thresholds with $n=4$ and 5 for Kr and Xe, respectively. The experiments were carried out using a pulsed, frequency comb-calibrated Fourier-transform-limited narrow-band long-pulse UV laser and a supersonic-beam apparatus [6].

The fine and hyperfine structures of np and nf Rydberg states of the nine and six natural isotopes of xenon and krypton, respectively have been analyzed in the range of principal quantum number n between 60 and 75 using multichannel quantum-defect-theory (MQDT). For the analysis of the fine and hyperfine structure we followed the formalism introduced for the $I=0$ isotopes by Lu and Lee [1] and Lu [2] and its extension in our group [3, 4, 5, 6] to treat the hyperfine structure in ^{83}Kr , ^{129}Xe and ^{131}Xe . Improved values of the ionization energies, the isotopic shifts and hyperfine coupling constants of $^{83}\text{Kr}^+$, $^{129}\text{Xe}^+$ and $^{131}\text{Xe}^+$ were derived from the MQDT analysis.

The same approach can be used to study the Rydberg states of Yb, both for the $I=0$ isotopes and $^{171}\text{Yb}^+(I=1/2)$ and $^{173}\text{Yb}^+(I=5/2)$. Low-lying excited electronic configurations of Yb^+ necessitate the inclusion of many more channels in the MQDT treatment [7, 8, 9]. We will present the current status on studies of the Rydberg spectrum of Yb which includes both experimental work of the Rydberg series accessible from the metastable $6s6p \ ^3P_0$ and $6s6p \ ^3P_2$ states and the MQDT analysis of the (ns), (np), (nd) and (nf) Rydberg series.

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Emergence of Synchronisation in a Driven-Dissipative Hot Rydberg Vapour

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Continuously driven, non-linear systems show complex behaviours such as bistability and self-oscillations. An interesting question regards the interplay of many self-oscillating entities with coupled dynamics due to an interaction between the individual oscillators. Such coupled dynamics have first been described by Huygens, who studied two coupled pendula, and have since been observed in many physical, chemical and biological systems. A collective response of self-oscillating ensembles have been observed in e.g. the applause of audiences or the flashing of fireflies, and is theoretically understood within the framework of synchronisation.

Recently, we have observed the emergence of synchronisation in a driven-dissipative hot Rydberg vapour [1]. We use a strongly-driven three-level ladder scheme in Rb, where we couple the intermediate $5P_{3/2}$ state to a Rydberg state. This introduces Rydberg-Rydberg interactions and collisional ionisation processes in the vapour and leads to complex interplay between the atoms. The synchronised state of our system manifests itself as oscillations of the transmission of the probe beam through the atomic vapour for a range of control parameters. We have a large range within which we can tune these control parameters, such as the laser detunings, interaction strengths, and mean atomic spacing. This, together with the fast oscillation frequencies on the order of 10 kHz, allow for an exploration of the synchronisation transition over a large parameter space and with many coupled oscillators.

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Precise microwave spectroscopy and hyperfine structure measurement of cesium nP_J Rydberg states

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Precise measurements of the fine and hyperfine energy levels of Rydberg states and their quantum defects play a role in testing atomic-structure and quantum-defect theories [1], as well as in applications of Rydberg-atom-based metrology [2] and Rydberg molecules. In this talk, we present a high-resolution microwave spectroscopy of $nS_{1/2} \rightarrow nP_J$ ($n = 41 - 55$) Rydberg transitions [3, 4] in a cold cesium atomic gas. The laser prepared nS state and microwave coupled nP state are detected by the state selective field ionization technique. A microwave field with 30- μ s duration couples the $nS \rightarrow nP$ transition, yielding a 35-kHz linewidth spectroscopy that approaches the Fourier limit, which allows us to resolve the hyperfine structure of nP_J states. In Fig. 1, we present the microwave spectroscopy of $41S_{1/2} \rightarrow 41P_{3/2}$ transition, where the hyperfine structures of $41P_{3/2}$ is clearly distinguished. With these narrow linewidth microwave spectroscopy, we extract the quantum defect of nP_J Rydberg states. Furthermore, we obtain the hyperfine splittings of nP_J states and determine the magnetic dipole HFS coupling constant A_{HFS} for $P_{1/2}$ state, and A_{HFS} and B_{HFS} for $P_{3/2}$ state. Systematic uncertainties caused by stray electromagnetic field, microwave field power, and Rydberg interaction are analyzed. This measurement is significant for the investigation of Rydberg electrometry and quantum simulation with dipole interaction involving the nP_J state.

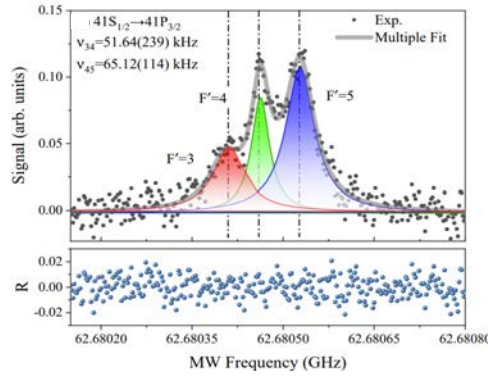


Figure 1: Measured microwave spectroscopy for a microwave field coupling the $41S_{1/2} \rightarrow 41P_{3/2}$ transition. Solid lines indicate multipeak Lorentz fittings, yielding the center frequency of hyperfine transition, marked with vertical dot-dashed lines. The bottom plots display the residuals, R , of the Lorentzian fit and spectrum.

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