UNIVERSIDAD DE GRANADA

EGAS

EGAS 55

Conference of the European Group on Atomic Systems

June 16 to 20, 2024

Granada, Spain

BOOK OF ABSTRACTS

EGAS

EGAS stands for European Group on Atomic Systems, formerly known as European Group on Atomic Spectroscopy (name changed in 2004). EGAS started in 1968 with the Caen Colloquium, known as EGAS 0. In 1969, the EGAS I was held at Laboratoire Aime Cotton in Orsay, with A. Kastler (Nobel Prize in Physics 1966) being the first EGAS chair. EGAS is a section of the Atomic, Molecular and Optical Physics Division (AMOPD) of the European Physical Society (EPS). For more information, please check the EGAS web page.

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Practical information

The EGAS 55 conference will be held at the Facultad de Ciencias of the Universidad de Granada:

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

Social events:

- Reception at the Gardens of Carmen de la Victoria on June 16 at 19:00.
- Alhambra Guided Tour on June 18, from 20:00 to 22:00, only for registered participants.
- Conference dinner at La Chumbera on June 19 at 20:00.

EGAS 55

Program

Sunday, June 16th

18:00 - 19:00 Registration at the Gardens of Carmen de la Victoria.

19:00 - Reception at the Gardens of Carmen de la Victoria.

Monday, June 17th

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

8:30 - 9:00 Opening at Aula Magna.

Plenary talks at Aula Magna

09:00 - 09:50 Anne L'Huillier
Attosecond pulses of light for the study of electron dynamics.

09:50 - 10:40 J. Ignacio Cirac
Quantum simulation in the NISQ era.

10:40 - 11:10 Coffee break.

Parallel Session: Monday M1 at Aula Magna

11:10 - 11:40 Javier Argüello-Luengo
Analog Simulators for High-Harmonic Generation in Atoms.

11:40 - 12:00 Gabriel Emperauger
Enhancing the capabilities of a quantum simulator based on Rydberg encoded qubits.

12:00 - 12:20 Vineesha Srivastava
Non-local multi-qubit quantum gates and entangled state preparation via a driven cavity.

12:20 - 12:40 Valentin Magro
Deterministic freely propagating photonic qubits with negative Wigner functions.

Parallel Session: Monday M2 at Salón de Grados.

11:10 - 11:40 Karolina Słowik
Light interactions with polar quantum systems

11:40 - 12:00 María Hernández Ruiz
Cavity-enhanced atomic magnetometer for micro-bio-magnetic measurements.

12:00 - 12:20 Ludovica Donati
Exploring noise-induced Fano interference in a hot vapor atomic gas.

12:20 - 12:40 Alexander Trachtmann
Rydberg excitation efficiency in nitric oxide using a three photon excitation scheme for a trace gas sensor.

12:50 - 14:20 Lunch

Parallel Session: Monday A1 at Aula Magna

14:20 - 14:50 David Ayuso
Ultrafast control over chiral sum-frequency generation.

14:50 - 15:10 Alicia Palacios
Two-photon double ionization of H_2 with sub-femtosecond laser pulses.

15:10 - 15:30 Andrés Ordóñez
Chiral coherent control of electronic population transfer with femtosecond pulses.

Parallel Session: Monday A1 at Salón de Grados.

14:20 - 14:50 Stefan Kuhr
Commensurate and incommensurate 1D interacting quantum systems

14:50 - 15:10 Krzysztof Pawlowski
Phenomena of Quasi-1D Quantum Dipolar Droplets in Weak and Strong Interaction Regimes.

15:10 - 15:30 Charles Creffield
Instabilities of superfluids in optical lattices under Floquet driving.

15:30 - 16:00 Coffee break

16:00 - 19:00 Poster session

Tuesday, June 18th

Plenary talks at Aula Magna

09:00 - 09:50 Pascale Senellart
Quantum light generation with semiconductor artificial atoms.

09:50 - 10:40 John M. Doyle
Ultracold molecules for quantum science and particle physics.

10:40 - 11:10 Coffee break.

Parallel Session: Tuesday M1 at Aula Magna

11:10 - 11:40 Sébastien Gleyzes
Circular Rydberg atoms of strontium.

11:40 - 12:00 Sylvain de Léséleuc
Ultrafast Rydberg experiments with ultracold atoms.

12:00 - 12:20 Eduardo Marín Bujedo
Direct laser cooling of Rydberg atoms with an isolated-core transition.

12:20 - 12:40 Niels Kjærgaard
Rydberg atomic polarimetry and electrometry of THz fields.

Parallel Session: Tuesday M2 at Salón de Grados.

11:10 - 11:40 Daniel Kienzler
Pure quantum state preparation and nondestructive readout of the hydrogen molecular ion.

11:40 - 12:00 Soroosh Alighanbari
A new frontier in fundamental physics: precision spectroscopy of H_2^+.

12:00 - 12:20 Charlotte Konig
High-precision measurements of single ions in the ALPHATRAP Penning trap Setup.

12:20 - 12:40 Daniel Rodríguez
From Doppler to quantum mass spectroscopy in a Penning trap.

12:50 - 14:20 Lunch

Parallel Session: Tuesday A1 at Aula Magna

14:20 - 14:50 Nils Madsen
Fundamental physics with antihydrogen.

14:50 - 15:10 Janko Nauta
Frequency metrology with antimatter.

15:10 - 15:30 Derwell Drapier
Sympathetic cooling of a Be^+ ion by a Coulomb crystal of $88Sr^+$ ions: a test bed for taming antimatter ions (GBAR).

Parallel Session: Tuesday A2 at Salón de Grados.

14:20 - 14:50 Tatiana Marchenko
Hard X-ray Auger spectroscopy probing electron dynamics.

14:50 - 15:10 Stefania Gravina
Investigation of the mercury intercombination line by means of comb-locked wavelength-modulated nonlinear spectroscopy.

15:10 - 15:30 Roland Wester
Optical spectroscopy and inelastic collisions of the laser-cooling candidate anion C_2^-.

15:30 - 16:00 Coffee break

Public Lectures at Aula Magna

16:00 - 16:50 Francesca Ferlaino
Supersolidity in the ultracold: when quantum gases behave as crystal and superfluid at the same time.

16:50 - 17:40 Miguel Ortega Titos
A geometric walk through the Alhambra.

19:40 - 22:00 Alhambra visit (only for registered participants).

Wednesday, June 19th

Plenary talks at Aula Magna

09:00 - 09:50 Eugenio Coronado
Molecular nanomagnets for quantum technologies.

09:50 - 10:40 Tanya Zelevinsky
Clocks and precision measurements with ultracold molecules.

10:40 - 10:50 EGAS General Assembly.

10:40 - 11:10 Coffee break.

Parallel Session: Wednesday M1 at Aula Magna

11:20 - 11:50 Thomas Pohl
Thermodynamics and ordered quantum phases of dipolar bosons.

11:50 - 12:10 Riccardo Cominotti
False vacuum decay via bubble formation in ferromagnetic superfluids.

12:10 - 12:30 Alessia Burchianti
Heteronuclear quantum droplets under the microscope.

12:30 - 12:50 Lafforgue Louis
Control and scattering properties in dipolar spin mixtures.

Parallel Session: Wednesday M2 at Salón de Grados.

11:20 - 11:50 Nicole Fabbri
Spins in diamond as an experimental toolbox for quantum thermodynamics.

11:50 - 12:10 Alex Guttridge
A programmable hybrid system of ultracold molecules and Rydberg atoms.

12:10 - 12:30 Tim Langen
Isotopologue-selective laser cooling of barium monofluoride molecules.

12:30 - 12:50 Delarue Thibault
Ultracold coherent control of molecular collisions at a Förster resonance.

12:50 - 14:20 Lunch

Parallel Session: Wednesday A1 at Aula Magna

14:30 - 15:00 Philipp Treutlein
Coupling quantum systems with a laser loop.

15:00 - 15:20 Laura Zarraoa
Quantum jump photodetector for narrowband photon counting with a single atom.

15:20 - 15:40 Vincent Mancois
Superoscillatory tweezer arrays for subwavelength trapping and manipulation of cold atoms.

Parallel Session: Wednesday A2 at Salón de Grados.

14:30 - 15:00 Henrik Stapelfeldt
The primary steps of ion solvation.

15:00 - 15:20 Miranda Nichols
High resolution spectroscopy of the atomic Sn^- system.

15:20 - 15:40 Adrien Poindron
Experimental demonstration of the coupling of trapped ions to a nano-wire.

15:45 - 16:15 Coffee break.

16:00 - 18:30 Poster session.

20:00 - Conference dinner at La Chumbera

Address: Camino de Sacromonte, 107, 18010, Granada

Thursday, June 20th

Both sessions at Aula Magna

09:30 - 10:00 Peter Schmelcher
Ultralong-range Rydberg molecules: Non-adiabatic interactions, synthetic dimensions and dynamics.

10:00 - 10:30 Edvardas Narevicius
Collisions with cold molecules: Tomography of Feshbach resonances.

10:30 - 11:00 Coffee break.

11:00 - 11:30 Leticia Tarruell
Exploring supersolidity with spin-orbit coupled Bose-Einstein condensates.

11:30 - 12:00 Daniel Barredo
Exploring quantum magnetism with Rydberg atom arrays.

12:00 - 12:30 Francesco S. Cataliotti
Quantum operations on an atom chip.

12:30 - 12:40 Closing

EGAS 55

Plenary Talks
Abstracts

Attosecond pulses of light for the study of electron dynamic

Anne L'Huillier

Lund University, Lund, Sweden

When an intense laser interacts with a gas of atoms, high-order harmonics are generated. In the time domain, this radiation forms a train of extremely short light pulses, of the order of 100 attoseconds. Attosecond pulses allow the study of the dynamics of electrons in atoms and molecules, using pump-probe techniques. This presentation will highlight some of the key steps of the field of attosecond science.

Quantum Simulation in the NISQ era

J. Ignacio Cirac

Max-Planck-Institut für Quantenoptik, Garching, Germany

Advancements in quantum computing have enabled the development of small-scale quantum computers and simulators that adhere to the principles of quantum physics. Despite their rapid progress, those devices are not yet flawless and errors accumulate, posing serious challenges to their application to relevant problems. In this talk I will review the field of quantum simulation, focusing on platforms based on cold atoms. Then, I will address the question of how errors affect the results of both quantum computations and the simulation of quantum many-body systems. In particular, I will present several quantum simulation algorithms, and discuss the potentiality of displaying quantum advantage in the presence of imperfections.

Quantum light generation with semiconductor artificial atoms

Pascale Senellart

Université Paris-Saclay, CNRS, Centre for Nanosciences and Nanotechnology, 91120 Palaiseau, France
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Single and entangle photons are cornerstone of many applications ranging from quantum computing to quantum networks, offering many degrees of freedom to encode the information. Semiconductor quantum dots are artificial atoms that, over the years, have been shown to be excellent sources of quantum light.

In this talk, I will first present the key ingredients of our quantum dot system and explain how, using the tools of cavity quantum electrodynamics and all the possibilities offered by semiconductor nano-processing, they can generate single photons at unparalleled rates and near unity quantum purity [1, 2]. This allows us to perform small scale quantum information processing protocols [3, 4].

Our devices have become close to text-book quantum emitters and they also allow us to revisit the fundamental of spontaneous emission. For instance, we have shown that upon coherent excitation, the coherence imprinted on the atomic state results in the emission of quantum superposition of zero and one photon [5]. Such photon-number coherence alters the foundation of photon-photon linear interactions, introducing errors to standardized photon indistinguishability measurements and leading to new quantum interference and entanglement phenomena in linear quantum gates [6].

Finally, adding an electron in the quantum dot, we can exploit the optical selection rules where the electron spin state conditions the polarisation of the emitted photons. Doing so, we demonstrate the deterministically generation of entanglement between a spin and multiple photons, thereby unlocking a critical knob for measurement-based quantum computing or quantum networks [7].

References

[1] *N. Somaschi, V. Giesz et al, Nature Photonics 10, 340-345, (2016).*

[2] *S. E. Thomas et al. Physical review letters 126 (23), 233601 (2021).*

[3] *M. Pont et al. Phys. Rev. X 12, 031033 (2022).*

[4] *N. Maring et al., Nature Photonics 2024. https://doi.org/10.1038/s41566-024-01403-4 .*

[5] *J. Loredo et al, Nature Photonics 13, 803 (2019).*

[6] *I. Maillette de Buy Wenniger et al. arXiv:2401.01187.*

[7] *N. Coste et al., Nature Photonics (2023).*

Ultracold molecules for quantum science and particle physics

John M. Doyle

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https://projects.iq.harvard.edu/jdoyle/home

Polar molecules, due to their intrinsic electric dipole moment and their controllable complexity, are a powerful platform for precision measurement searches for physics beyond the standard model (BSM) and, potentially, for quantum simulation/computation. This has led to many experimental efforts to cool and control molecules at the single quantum state level. I will present an overview of my group's work with ultracold molecules, which includes work from last year demonstrating entanglement and iSWAP operations with individual CaF molecules in optical tweezers, and work from this year on polyatomic molecules. Polyatomic molecules have attracted new focus as potential novel quantum resources with distinct advantages - and challenges - compared to both atoms and diatomic molecules. I will discuss features of polyatomic molecules that can be used in quantum simulation/computation, the search for BSM physics, and ultracold chemistry. I will discuss our results on the laser cooling of polyatomic molecules into the ultracold regime, including the laser cooling of the polyatomic molecules. We realize a novel, blue-detuned MOT for CaOH, a tweezer array of single CaOH molecules, and a robust MOT for SrOH. Finally, if time permits, I will discuss recent measurements on spin precession in a metastable vibrational bending mode of CaOH, and the use of SrOH and RaOH for future experiments searching for the electron electric dipole moment, a probe for BSM physics in the > 10 TeV range, as well as Dark Matter.

Clocks and precision measurements with ultracold molecules

*Tanya Zelevinsky**

Columbia University, New York, USA

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Precise atomic spectroscopy has been instrumental for building our understanding of the physical world. The level of precision entered a new realm with the advent of laser cooling and trapping as well as stable light sources. In recent years we have been able to extend the ultrahigh spectroscopic precision, or atomic clock technology, to more complex quantum particles such as diatomic molecules. The ability to quantify molecular degrees of freedom, for example their vibrational motion, with nearly atomic-clock level resolution shines a light on the molecules' previously unseen properties. It also suggests new possibilities for uncovering fundamental aspects of physical interactions, including improved tests of Newtonian gravity at the nanometer scale.

Molecular nanomagnets for quantum technologies

Eugenio Coronado

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Spins embedded in solid hosts provide one of the simplest platforms to encode quantum bits. Among the different candidates, chemically designed magnetic molecules stand out for several reasons [1]. Besides being microscopic, thus reproducible and intrinsically quantum, they represent the smallest structure in which the relevant properties can be tuned by adequately choosing the molecular composition and structure. Even more, it enables scaling up computational resources within each molecule, by making use of multiple internal spin states or by wiring up different molecules into a scalable architecture. Here, I will show how this molecular approach can be exploited to design robust molecular quantum spin systems showing enhanced decoherence [2], allowing to control the spin state through an external electric field [3], hosting more than one spin qubit in order to implement quantum logic gates [4], or integrated into microwave superconducting resonators for reading out the spin state and for introducing effective interactions [5].

References

[1] E. Coronado, Nat. Rev. Mater. **5**, 87-104 (2020).

[2] A. Gaita-Ariño, F. Luis, S. Hill, and E. Coronado, Nat. Chem. **11**, 301-309 (2019).

[3] J. Liu et al, Nat. Phys. **17**, 1205-1209 (2021).

[4] M. D. Jenkins et al, Phys. Rev. B **95**, 064423 (2017).

[5] I. Gimeno et al, Phys. Rev. Appl. **20**, 044070 (2023).

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Public Lectures Abstracts

Supersolidity in the ultracold: when quantum gases behave as crystal and superfluid at the same time

Francesca Ferlaino

Institute for Experimental Physics, Universität Innsbruck, Austria

&

Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Science

Quantum physics frequently gives rise to conceptual paradoxes that defy our classical intuition. In many-body quantum systems, interactions are key, especially when they dominate over kinetic energy. Their form and strength crucially define the existing strongly-correlated quantum phases of matter and dictate phenomena beyond the classical regime. Dipolar interactions, particularly relevant in strongly magnetic atoms, are fundamentally distinct from the typical van der Waals interactions in neutral atoms. Their orientation-dependence and non-locality enable the emergence of novel phases of matter, from ultra-dilute quantum droplets to supersolid phases in which macroscopically coherent quantum gases self-organize in space to produce ordered density wave with energy cost approaching zero. This talk will retrace the new phenomena, which have been observed with quantum degenerate gases of erbium and dysprosium atoms from the perspective of the Innsbruck experiments.

A Geometric walk through the Alhambra

Miguel Ortega Titos

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The Alhambra of Granada is worldwide famous, among other reasons, for its beautiful decorations, which are spread out in walls, windows and ceilings. In this talk, we will discover some of the mathematical secrets used by the Nasrid artisans and artists: the use of proportions, unique Nasrid decorative elements and the examples of crystallographic groups.

EGAS 55

Invited Talks Abstracts

Analog Simulators for High-Harmonic Generation in Atoms

Javier Argüello-Luengo, Javier Rivera-Dean, Philipp Stammer, Andrew S. Maxwell, David M. Weld, Marcelo F. Ciappina, and Maciej Lewenstein*

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Departament de Física, Universitat Politècnica de Catalunya, Campus Nord B4-B5, 08034 Barcelona, Spain

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The demanding experimental access to the ultrafast dynamics of materials challenges our understanding of their electronic response to applied strong laser fields. For this purpose, trapped ultracold atoms with highly controllable potentials have become an enabling tool to describe phenomena in a scenario in which some effects are more easily accessible and 12 orders of magnitude slower [1]. In this work, we introduce a mapping between the parameters of attoscience platforms and atomic cloud simulators and propose an experimental protocol to access the emission spectrum of high-harmonic generation (HHG), a regime that has so far been elusive to cold-atom simulation [2] (see Fig. 1). We show that these platforms offer a unique opportunity to access and measure the emission spectrum of HHG through absorption measurements [3]. Furthermore, it simulates the physical response of a *single-atom* target. This is in contrast with real experiments, where thousands of atoms are simultaneously driven to collect enough photons to resolve the spectrum, which challenges phase-matching conditions when a large ionization occurs under strong fields. As we illustrate, the benchmark offered by these simulators can provide new insights into the conversion efficiency of extended and short nuclear potentials, as well as the response to applied elliptical polarized fields or ultrashort few-cycle pulses.

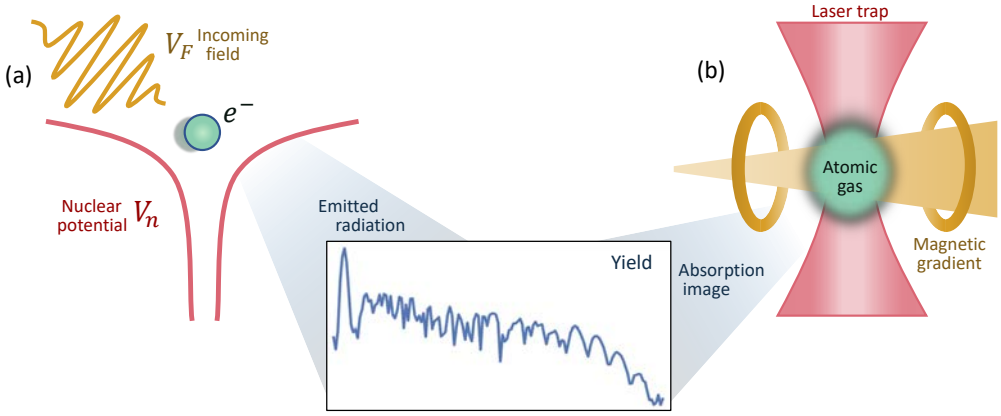

Figure 1: Schematic representation of HHG in atoms (a), and the proposed analog simulator (b). In (a) an ultrafast incoming field (brown) accelerates an electron (green), that is originally trapped by the nuclear Coulomb potential of the atom (red). The resulting oscillation of the charge emits radiation of characteristic harmonic frequencies (inset in blue). The same emission yield can be simulated on the simulator (b), where the characteristic frequencies are retrieved through absorption images of an atomic gas (green) that is trapped by a laser potential (red), and addressed by an external magnetic gradient that is tuned over time (brown).

References

[1] S. Sala, J. Förster, and A. Saenz, Ultracold-atom quantum simulator for attosecond science, Phys. Rev. A 95, 11403 (2017).

[2] R. Senaratne, et al., Quantum simulation of ultrafast dynamics using trapped ultracold atoms, Nat. Commun. 9, 2065 (2018).

[3] Javier Argüello-Luengo, Javier Rivera-Dean, Philipp Stammer, Andrew S. Maxwell, David M. Weld, Marcelo F. Ciappina, and Maciej Lewenstein, PRX Quantum 5, 010328 (2024).

Light interactions with polar quantum systems

Piotr Gładysz[1], *Niya Petkova*[2], *Giovanni Scala*[3], *Piotr Wcisło*[1], *Francesco Pepe*[4], *Paolo Facchi*[4], *Saverio Pascazio*[4], *Karolina Słowik*[*1]

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Spatial symmetries, quantified in terms of multipolar transition moments, determine the optical properties of atomic systems. Their values are related to selection rules indicating which transitions may occur in a quantum system. On the contrary, permanent multipolar moments are routinely neglected as causing trivial shifts in the energy spectrum of the system. This contribution studies the light-matter interaction regimes in which this commonly held practice is wrong.

A paradigmatic quantum effect modified in polar quantum systems is the periodic Rabi population transfer. As it occurs between eigenstates sustaining dipole moments it gives rise to an additional oscillating dipole being a radiation source at Rabi frequency [1, 2]. This frequency can be controlled in a broad spectral range, potentially giving rise to all-optically tunable coherent radiation sources [3, 4].

Permanent dipole moments also affect the light-matter interaction strength. For non-polar systems, the interaction strength scales linearly with the amplitude of the driving electric field. For polar systems in strong fields, this scaling may be modified, suggesting a coherent dynamics regime in high-intensity fields, robust to strong spatial field variations.

References

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[3] I. Chestnov, V. A. Shahnazaryan, A. P. Alodjants, I. A. Shelykh, ACS Photonics **4**, 2726-2737 (2017).

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Ultrafast control over chiral sum-frequency generation

Josh Vogwell[1], Laura Rego[1], Olga Smirnova[2,3] and David Ayuso[1,2,3*]

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Just like our hands, chiral molecules exist in pairs of opposite "mirror twins", called enantiomers, which behave identically unless they interact with another chiral object. Distinguishing them is vital, e.g. as most biomolecules are chiral, but also challenging. Traditional chiral spectroscopy relies on the spatial helix that circularly polarized light draws in *space*. However, the pitch of this helix is orders of magnitude larger than the molecules, which leads to tiny enantiosensitivity ($< 0.1\%$). One can overcome this limitation by creating *synthetic* chiral light [1,2], where the tip of the electric-field vector draws a chiral trajectory in *time*, enabling 100% enantiosensitivity. Here show how we can bring this giant chiral sensitivity to the perturbative regime: by combining chiral sum-frequency generation (SFG) and third-harmonic generation (THG).

Chiral SFG [3] uses two laser beams with frequencies $\omega_1 \neq \omega_2$, wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$, and polarizations $\hat{\mathbf{e}}_1$ and $\hat{\mathbf{e}}_2$, to drive a second-order response with frequency $\omega_1 + \omega_2$ and polarization $\hat{\mathbf{e}}_1 \times \hat{\mathbf{e}}_2$, leading to emission of light along $\mathbf{k}_1 + \mathbf{k}_2$. SFG in randomly oriented molecules is symmetry-allowed only if they are chiral, and driven by purely electric-dipole interactions. However, the intensity of SFG is not enantiosensitive – the molecular handedness remains hidden in its phase.

We can achieve full control over the intensity of SFG in randomly oriented chiral molecules [4] by making the driving field *locally* chiral [1,2]. Our setup (Fig. 1a) leads to emission of SFG and THG in the same direction (Fig. 1b). By controlling the two-color phase delay (Fig. 1a), we control the field's local chirality, and thus the enantiosensitive interference. As a result, we can maximize emission of light at 266nm in one molecular enantiomer while fully quenching it in its mirror twin (Fig. 1c). Our approach enables ultrafast imaging of molecular chirality via low-order nonlinear processes, which require gentle laser intensities, thus creating exciting opportunities for efficient chiral recognition in the liquid phase, the natural medium of biological molecules, or in amorphous chiral solids.

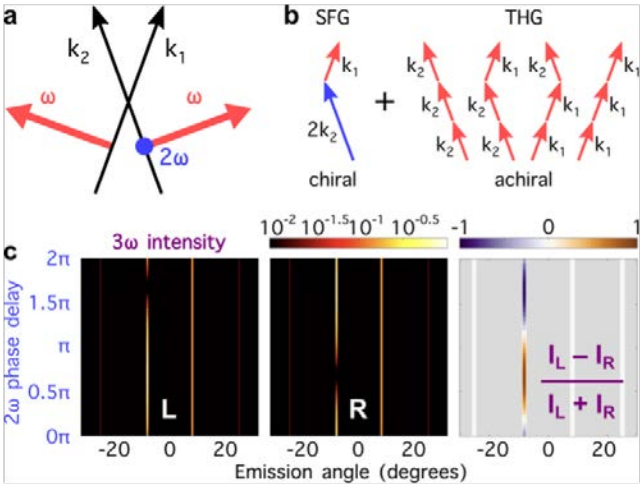

Figure 1: **a,** Non-collinear setup combining linearly polarised ω and 2ω colors. **b,** Multiphoton diagrams of momentum conservation in chiral SFG (left) and achiral THG (right). The induced polarization associated with SFG has the same amplitude and opposite phase in opposite enantiomers, $\mathbf{P}^L_{SFG} = -\mathbf{P}^L_{SFG}$, whereas $\mathbf{P}^L_{THG} = -\mathbf{P}^L_{THG}$. **c,** Intensity emitted from left/right propylene oxide at frequency 3ω (266nm). TDDFT results; laser parameters: ω=0.057au (800nm), opening angle 25°, $I_\omega = 3\cdot10^{12}\text{Wcm}^{-2}$, $I_{2\omega} = 7\cdot10^{11}\text{Wcm}^{-2}$, pulse duration 7fs, see [4] for more details.

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[2] D Ayuso et al, *Nature Commun* **12**, 3951 (2021)
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Commensurate and incommensurate 1D interacting quantum systems

*Christopher Parsonage, Paul Schroff, Lennart Koehn, Arthur La Rooij, Andrea Di Carli, Callum Duncan, Andrew Daley, Elmar Haller, Stefan Kuhr**

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Single-atom imaging resolution of many-body quantum systems in optical lattices is routinely achieved with quantum-gas microscopes. Key to their great versatility as quantum simulators is the ability to use engineered light potentials at the microscopic level. In our recent work, we employ dynamically varying microscopic light potentials in a quantum-gas microscope, created by a digital mirror device (DMD), to study commensurate and incommensurate 1D systems of interacting bosonic Rb atoms [1]. Such incommensurate systems are analogous to doped insulating states that exhibit atom transport and compressibility. Initially, a commensurate system with unit filling and fixed atom number is prepared between two potential barriers. We deterministically create an incommensurate system by dynamically changing the position of the barriers such that the number of available lattice sites is reduced while retaining the atom number. Our systems are characterised by measuring the distribution of particles and holes as a function of the lattice filling, and interaction strength, and we probe the particle mobility by applying a bias potential. Our results provide the foundation for preparation of low-entropy states with controlled filling in optical-lattice experiments.

In a different strand of work, we have been using a phase-modulating spatial light modulator (SLM), to generate arbitrary light potentials holographically with measured efficiencies between 15 and 40% and an accuracy of $< 2\%$ root-mean-squared error [2]. Key to the high accuracy is the modelling of pixel crosstalk of the SLM on a sub-pixel scale which is relevant especially for large light potentials.

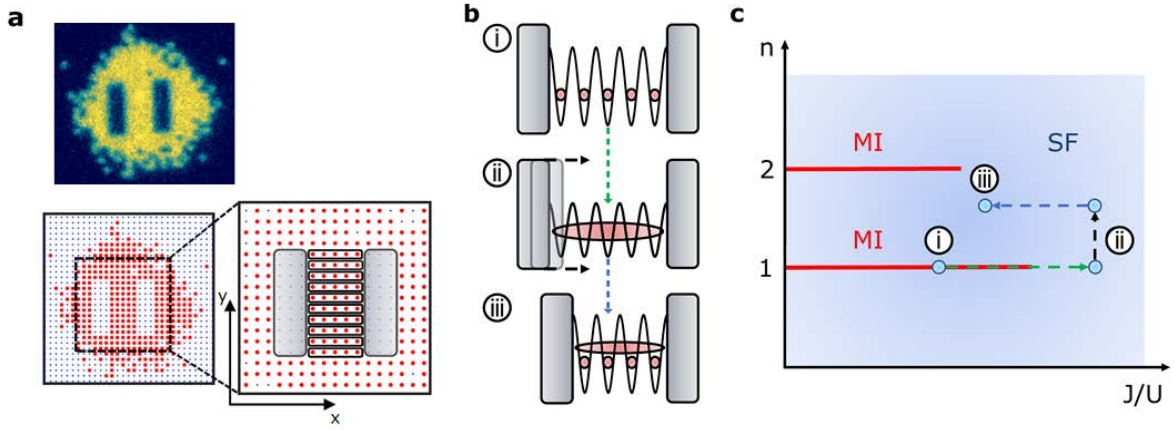

Figure 1: **a** Top: fluorescence image of a Mott insulator of ^{87}Rb atoms in the presence of two repulsive potential barriers. Bottom: Corresponding atom distribution showing individual 1D systems with five atoms between the the repulsive potential. **b**, Preparation of an incommensurate (doped) 1D quantum system by (i) preparation of a Mott insulating state, (ii) transition to the superfluid regime, and reduction of the number of lattice sites by moving the potential barrier, (iii) transition into the strongly interacting regime. **c** Phase diagram for the 1D Bose-Hubbard model [1]

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Circular Rydberg Atoms of Strontium

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

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

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

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

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Pure quantum state preparation and nondestructive readout of the hydrogen molecular ion

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I will present our latest results, implementing pure quantum state preparation, coherent manipulation, and non-destructive state readout of the hydrogen molecular ion H_2^+.

The hydrogen molecular ion H_2^+ is the simplest stable molecule, and its structure can be calculated ab-initio to high precision. However, challenging properties such as high reactivity, low mass, and the absence of rovibrational dipole transitions have thus far strongly limited spectroscopic studies of H_2^+.

We trap a single H_2^+ molecule together with a single beryllium ion using a cryogenic Paul trap apparatus, achieving trapping lifetimes of 11 h and ground-state cooling of the shared axial motion [1]. With this platform we have recently implemented *Quantum Logic Spectroscopy* of H_2^+. We utilize helium buffer-gas cooling to prepare the lowest rovibrational state of ortho-H_2^+ (rotation $L = 1$, vibration $\nu = 0$). We combine this with quantum-logic operations between the molecule and the beryllium ion for the preparation of single hyperfine states and non-destructive readout, achieving a combined state-preparation and readout fidelity of $\approx 70\%$. We demonstrate Rabi flopping on several hyperfine transitions using stimulated Raman transitions and microwaves. Utilizing a magnetic field insensitive hyperfine transition driven with a microwave, we perform a proof-of-principle spectroscopy and achieve a statistical uncertainty of 2 Hz after averaging 37 minutes (including calibrations of quantum logic operations, etc).

Our results pave the way for many high-precision spectroscopy studies of H_2^+, which would enable tests of theory, metrology of fundamental constants, and the implementation of an optical molecular clock based on the simplest molecule.

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Fundamental Physics with Antihydrogen

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Antihydrogen, the bound state of a positron and an antiproton, calculable from first principles, is a uniquely well suited system for searching for discrepancies between matter and antimatter that could explain the baryon asymmetry of the universe.

The ALPHA collaboration has for more than a decade been able to trap antihydrogen atoms [1] allowing the first detailed studies of internal states [2, 3]. The ability to trap anti atoms has evolved significantly since the first demonstration in 2010, such that we now not only trap the anti-atoms, but continuously accumulate them over many hours [4]. Additional techniques (e.g. [5]) have allowed accumulating many thousands of anti-atoms at rates of about a thousand atoms per hour. The ALPHA experiment is thus uniquely suited to continue to expand our multi pronged experiments on antihydrogen.

These developments, together with the recent addition of laser-cooling [6] to the toolkit will allow us to probe the internal structure of antihydrogen to even greater precision that we've accomplished so far, and start detailed, eventually direct, comparisons with hydrogen, as well as start to extracting fundamental parameters such as the (anti)Rydberg constant, the antiproton charge radius and the (anti)Lamb shift.

Additionally, we have only just started exploiting our vertical antihydrogen trap, something that allowed us the first observation of the influence of gravity on antimatter [7], and that, in particular with the enhancements above, should allow us to steadily increase the precision of these measurements to compete with measurements performed with matter systems.

I will discuss the key techniques we have developed to have thousands of anti-atoms available for study, and discuss some of our most interesting measurements to date, focussing on the challenges and advantages of working with small samples of trapped anti-atoms when trying to elucidate their internal structure and their response to the earths gravitational field.

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Hard X-ray Auger spectroscopy probing electron dynamics

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A remarkable progress in the synchrotron technology provides nowadays a wealth of information on the relaxation mechanisms of core-exited systems through high energy-resolution electron and X-ray spectroscopy [1]. In this talk I will discuss applications of Auger spectroscopy in sulfur-containing organic gas-phase molecules and solid-state polymers, providing access to the processes occurring on the time scale determined by the S 1s core-hole lifetime of about 1 fs.

In the first example, we use Auger spectroscopy to explore post-collision interaction in gas-phase thiophene in comparison to solid thiophene-based polymers: polythiophene (PT) and poly(3-hexylthiophene-2,5-diyl), also known as P3HT. Following S 1s ionisation, the Coulomb interaction between the photoelectron, the Auger electron and the residual doubly-charged ion results in distortion and energy shift of the photoelectron and Auger electron spectral lines. We discover that this effect is amplified in solid polymers compared to gas-phase molecules due to modification of post-collision interaction by the polarisation screening and photoelectron scattering in the condensed medium [2].

In the second example, we apply resonant Auger spectroscopy to explore charge transfer in thiophene-based PT and P3HT polymers upon resonant excitation at the S 1s-edge. Our combined experimental and theoretical investigation established that the dominant mechanism of charge transfer in polymer powders and films consists of electron delocalisation along the polymer chain occurring on the low-femtosecond time scale [3].

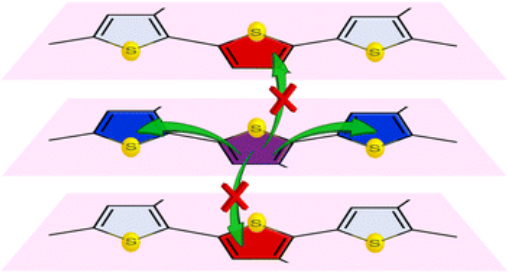

Figure 1: Sketch of the excited thiophene ring (purple) and its nearest neighbours along the chain (blue) and in the layers above and below (red) in P3HT film. The green arrows show that only the intra-chain charge transfer is possible.

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Thermodynamics and ordered quantum phases of Dipolar Bosons

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Bosonic quantum many-particle systems with long-range dipolar interactions display remarkable behaviour, such as the formation of quantum droplets and the emergence of supersolid phases with a rich spectrum of complex density-wave patterns. In particular, the anisotropic nature of dipole-dipole interactions highlights the role of fluctuations and, thereby, provides unique opportunities to scrutinize theoretical descriptions of quantum effects beyond simple meanfield pictures. Experiments on ultracold atoms with large magnetic dipoles and, more recently, the realization of ultracold polar molecules offer an excellent laboratory platform for exploring such phenomena and improving our understanding of long-range interacting quantum gases.

Here, we consider theoretically the formation of ordered phases of dipolar Bosons under conditions of recent experiments with magnetic atoms as well as polar molecules. Special emphasis will be placed on the detailed role of quantum fluctuations, confinement and geometry as well as temperature effects for the formation ordered phases in extended systems of dipolar Bosons.

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Spins in diamond as an experimental toolbox for quantum thermodynamics

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Elucidating thermodynamics processes in nanoscale devices requires to take into account fluctuations and quantum effects in work and heat transfers. I will discuss how we can use spins associated with nitrogen-vacancy centers in diamond as a novel toolbox for quantum thermodynamics at the nanoscale, exploiting their exquisite control and long coherence time, as well as our ability to tailor the interaction with their environment. I will show how we characterize genuinely nonclassical multi-time correlations in a diamond spin qutrit under a unitary quantum work process using projective measurements with no ancillas. Interestingly, we observe peaks in the work extraction associated to anomalous energy exchanges due to the underlying negativity of the quasiprobability work distribution [1]. I will also show how we quantify the contribution to non-equilibrium entropy production stemming from the quantum coherence content in the initial state of a spin qubit exposed to both coherent driving and dissipation. This result is underpinned by the formulation of a generalized fluctuation theorem designed to track the effects of quantum coherence [2].

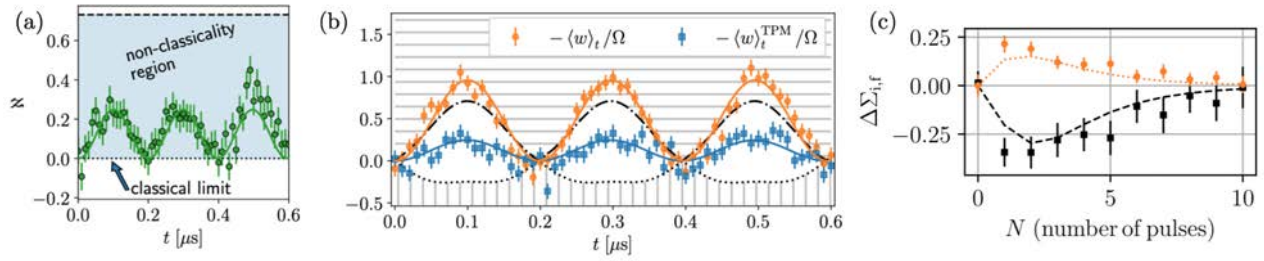

Figure 1: (a) Negativity of the quasiprobability work distribution of a diamond spin qutrit under a unitary quantum work process (experimental data and simulation). The non-classical region (blue area) is bounded from above by $\sqrt{d}-1$ (dashed line), where $d=3$ is the dimension of the system's Hilbert space. (b) Average unperturbed extracted work (orange dots), and average extracted work in a two-point-measurement (TPM) scheme (blue squares). The striped regions on top (bottom) indicate violations of stochastic work extraction (injection) bounds, achievable only for non-zero negativity. (c) Coherence-affected irreversible entropy production $\Delta\Sigma_{i,f}$ in a diamond spin qubit when a dissipative channel is opened in the form of repeated optical interactions. Black squares and dashed line: $\Delta\Sigma_{1,1}=\Delta\Sigma_{0,1}$; orange bullets and dotted line: $\Delta\Sigma_{0,0}=\Delta\Sigma_{1,0}$.

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Coupling quantum systems with a laser loop

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Many of the breakthroughs in quantum science and technology rely on engineering strong Hamiltonian interactions between quantum systems. Typically, strong coupling relies on short-range forces or on placing the systems in high-quality electromagnetic resonators, which restricts the range of the coupling to short distances. In this talk I will show how a loop of laser light can generate Hamiltonian coupling over a distance [1] and report experiments using this approach to strongly couple a nanomechanical membrane oscillator and an ultracold atomic spin ensemble across one meter in a room-temperature environment [2]. We observe spin-membrane normal mode splitting, coherent energy exchange oscillations, two-mode thermal noise squeezing, and dissipative coupling with exceptional points [2]. We furthermore realize an optical coherent feedback loop and use it for cooling of the membrane vibrations [3, 4]. Our experiments demonstrate the versatility and flexibility of light-mediated interactions, a powerful tool for quantum science that offers many further possibilities and is readily applicable to a variety of different systems.

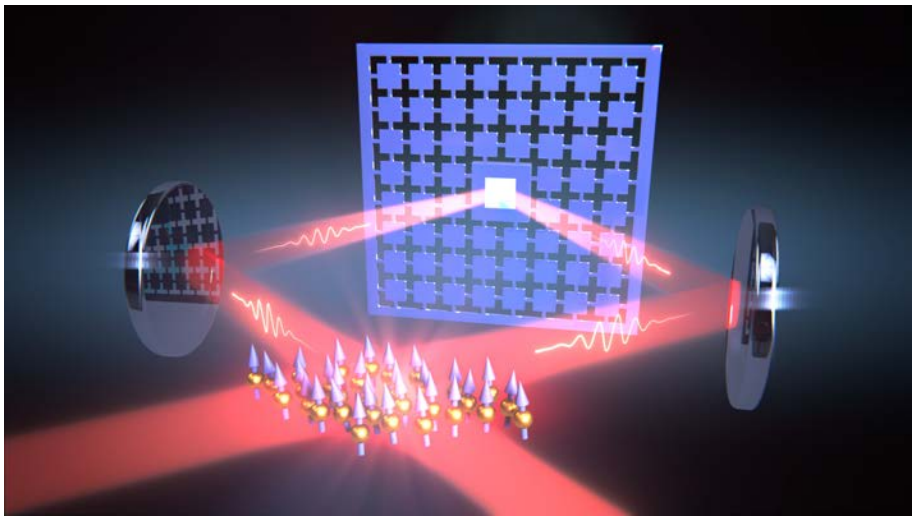

Figure 1: A loop of laser light couples the vibrations of a nanomechanical membrane to the spins of atoms.

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The primary steps of ion solvation

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Solvation is an omnipresent process both in our daily life and in the natural sciences. At the atomic level, the primary steps of solvation are the attraction and binding of ions or molecules of a solute to molecules or atoms of a solvent. Hitherto, these steps have not been observed in real time.

I will present recent experimental results that have enabled us to observe the solvation dynamics of a single alkali cation ion in liquid helium with atomic resolution and on the natural femtosecond time scale. A single Na^+ is created instantly at the surface of a liquid He nanodroplet and we measured in real time the gradual attachment of individual He atoms to the ion. In addition, we determined how fast the solvent-solute binding energy is dissipated from the local region around the alkali ion [1].

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Ultralong-range Rydberg molecules: Non-adiabatic interactions, synthetic dimensions and dynamics

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Ultralong-range Rydberg molecules are highly asymmetric molecules with exaggerated properties. They consist of one or several ground state atoms which are bound to a Rydberg atom thereby yielding bond lengths of the order of many hundred nanometers to micrometers for principal quantum numbers $n = 30 - 100$. There exist non-polar (low-angular momentum) as well as polar (large angular momentum) molecular states with the latter possessing huge electric dipole moments. The corresponding potential energy surfaces are highly oscillatory and possess many equilibria which reflect the many nodes and oscillations of the underlying Rydberg wave function. We report here on some recent developments in the field covering several aspects of non-adiabatic interactions and effects and quantum dynamics for this exotic species. We show that the principal quantum number can be seen as a synthetic dimension which leads to conical intersections even for diatomic Rydberg molecules [1]. The latter govern the collisional dynamics of a ground state atom and a Rydberg atom specifically in ultracold $l-$changing processes. We explore the interaction of a d-state and the energetically close-by trilobite state [2], exhibiting avoided crossings that lead to the breakdown of the adiabatic Born-Oppenheimer approximation. A coupled-channel approach is used to obtain the corresponding spectrum that exhibits stark differences in comparison to the BO spectra, such as the existence of above-threshold resonant states without any adiabatic counterparts, and a significant rearrangement of the spectral structure as well as the localization of the eigenstates. Vibronic interactions in the butterfly and trilobite states are identified and classified [3]. To trigger molecular wave packet dynamics we perform quenches of an external electric field impacting the internuclear as well as angular motion of the molecule [4]. Depending on the initial state, we observe radial intrawell and interwell oscillations as well as angular oscillations and rotations. Opportunities to control the molecular configuration are identified, a specific example being the possibility to superimpose different molecular bond lengths by a series of periodic quenches of the electric field.

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Collisions with cold molecules: Tomography of Feshbach resonances

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During collisions coupling between relative and internal atomic and molecular degrees of freedom leads to the formation of Feshbach resonances. The large phase space volume that particles explore in this metastable scattering state supports interference between many different quantum pathways that include inelastic and reactive processes. We present a new method that allows us to measure simultaneously all the quantum channels for Feshbach resonances that appear in collisions between vibrationally excited H_2^+ ion and noble gas atoms. Our quantum state mapping is based on ion-electron coincidence velocity map imaging spectroscopy.

Exploring supersolidity with spin-orbit coupled Bose-Einstein condensates

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Supersolidity is a counter-intuitive phase of matter that spontaneously breaks both gauge and translation symmetry, and combines the frictionless flow of a superfluid and the crystalline structure of a solid. Until now supersolids have only been realized in Bose-Einstein condensates, exploiting three different ingredients: dipolar interactions, cavity-mediated interactions, and spin-orbit coupling. The properties of dipolar and cavity supersolids have been explored in detail, showing common features but also important differences concerning their excitation spectra. In contrast, all spin-orbit coupled supersolids realized to date were very fragile, and could only be probed indirectly. This led to contradictory opinions concerning the properties of their modulated density profile, also known as the stripe pattern, and of their collective excitations.

We have leveraged the tunable interaction properties of potassium atoms to realize robust supersolids in a spin-orbit coupled Bose-Einstein condensate, and to observe for the first time *in situ* their modulated density profiles. We experimentally demonstrate that, unlike in cavity supersolids, the supersolid stripe spacing is not fixed: it varies with the spin-orbit coupling strength and hosts a stripe compression mode. Moreover, we measure the softening of the stripe compression mode frequency with increasing spin-orbit coupling strength, revealing in this way the supersolid phase transition. Our experiments establish spin-orbit coupled Bose-Einstein condensates as an attractive platform to investigate supersolidity, and provide an excellent starting point to explore its interplay with quantum fluctuations and external lattice potentials.

Exploring quantum magnetism with Rydberg atom arrays

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Rydberg atoms in arrays of optical tweezers open up new horizons for quantum simulation, computation, and metrology. In this talk, we will present an overview of this architecture and describe ongoing efforts to control Rydberg interactions for exploring various types of spin Hamiltonians and generating entanglement. We will review recent results on implementing the dipolar XY model with more than 100 spins to study quantum magnetism [1]. Different magnetic orders, arising from the ferromagnetic or antiferromagnetic nature of the interactions, will be examined. We will demonstrate how entanglement in the out-of-equilibrium dynamics of these systems can be harnessed to generate scalable spin squeezing [2]. Additionally, we will discuss how analyzing the spread of correlations enables us to measure the dispersion relations in the dipolar system [3], and provide some perspectives on future developments.

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Quantum Operations on an Atom Chip

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Atom Chips are an important simplification in the creation and manipulation of ultracold and degenerate atomic samples. In my laboratory, we take advantage of an Atom Chip set-up to create a Bose-Einstein condensate of Rubidium and manipulate its internal states to perform quantum operations.

The first set of experiments I report, takes advantage of the fivefold Hilbert space given by the magnetic sublevels of the $F = 2$ ground state to realise optimal time reversal routines. Each time-reversal transformation is attained by designing an optimal modulated radio frequency field, achieving, on average, an accuracy of around 92% in any performed test. This physically realises a quantum *undo* operation, i.e. even in a quantum scenario, the last performed operation can be time-reversed via the *undo* command so as to perfectly restore a condition in which any new operation, chosen by the external user, can be applied. I put forward a thermodynamic interpretation based on the Loschmidt echo. These findings are expected to promote the implementation of time-reversal operations in a real scenario of gate-based quantum computing with a more complex structure than the five-level system considered here [1].

In the second set of experiments, I compare the performance of a qu-bit implemented in the magnetic insensitive sublevels of the Rubidium ground state to that of a quantum-optics set-up and to a Rigetti quantum computer. The performance test is realised on a numerically optimized, via deep learning methods, quantum embedding protocol to efficiently classify classical data. It is found that the quantum embedding approach successfully works also at the experimental level and, in particular, we have been able to demonstrate how different platforms could work in a complementary fashion to achieve this task [2].

The reported results, realised with a relatively simple experimental procedure show the versatility of the Atom Chip approach in quantum technology contexts as quantum computing and quantum communications.

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EGAS 55

Contributed Talks Abstracts

Enhancing the capabilities of a quantum simulator based on Rydberg-encoded qubits

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Quantum simulation with arrays of trapped atoms has already shown fruitful results for the understanding of quantum many body phenomena, such as spin transport and magnetism [**?**]. In this abstract, I will present two recent works that extend the capabilities of a Rydberg-based quantum simulator. They have been developed in our experimental group of Palaiseau in collaboration with theoretical teams in University of Harvard and München (LMU).

First, I will show a technical improvement that makes it possible to perform local rotations on Rydberg-encoded qubits [**?**] – an operation which had been so far only demonstrated in the atomic ground state. It relies on a combination of local addressing beams and global microwave fields (Figure 1). This new technique allows us to measure multi-basis observables (such as chirality) and perform state tomography of 3-atom entangled states.

Second, I will present our ongoing work on trying to extend the range of spin models simulated by our platform, using non-diagonal second order Rydberg-Rydberg interactions. For example, the so-called $t - J$ model, describing antiferromagnetic insulators doped with holes, can be simulated using this approach [**?**].

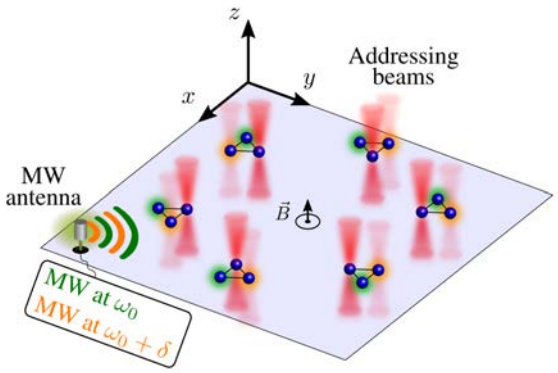

Figure 1: Sketch of the setup used for performing local rotations, using global microwave fields (yellow and green) and local addressing beams inducing controlled lightshifts (red).

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Non-local multi-qubit quantum gates and entangled state preparation via a driven cavity

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To enable scalable fault-tolerant quantum computation in the future and to enable usage of quantum error correction codes with non-local stabilizers, such as LDPC codes [2], it is highly desirable to have non-local quantum gates between multiple qubits. In this direction, we designed two new protocols [1] for implementing deterministic non-local multi-qubit quantum gates on qubits coupled to a common bosonic mode e.g. a cavity field. In contrast to previous proposals, our protocols only rely on a classical drive of the bosonic mode, while no external drive of the qubits is required. I will describe in detail our first protocol, where the state of the bosonic mode follows a closed trajectory in phase space and accumulates a geometric phase depending on the state of the qubits. This geometric phase gate can be used together with global single qubit gates to generate any Dicke state and any arbitrary superposition state in the Dicke subspace, including high- fidelity GHZ states, and metrologically useful states like the W state and symmetric state with $N/2$ excitations. We provide analytic solution for the qubit state and the phase acquired in the presense of relevant losses which allows for the calculation of averaged error rate of the protocol and the state preparation errors, which scale as $\sim N/\sqrt{C}$, with C the cooperativity and N the qubit number. Our protocols are applicable to a variety of systems, including atomic and molecular qubits coupled to optical or microwave cavities, for which I will discuss the estimates of gate fidelities and durations.

For more information, see Ref. [1]

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Deterministic freely propagating photonic qubits with negative Wigner functions

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The production of non-Gaussian Wigner-negative states is required for many protocols of quantum information processing [1]. Outside the microwave domain such photonics states have only been generated via stochastics processes with low efficiencies, which raises scalability issues when one tries to implement non trivial protocols.

Here, we will present the first fully-deterministic preparation of non-Gaussian Wigner-negative free-propagating optical quantum states[2]. In our setup, a small atomic cloud, placed inside a medium finesse optical cavity and driven to a highly-excited Rydberg state acts as a single two-level collective "superatom" [3]. We coherently control its internal state, then map it onto a free-propagating light mode to produce an optical qubit $\cos(\theta/2)\,|0\rangle + \sin(\theta/2)\,|1\rangle$ encoded as a quantum superposition of 0 and 1 photons. Its single-photon character is revealed by photon-correlation measurements showing strong antibunching with only a residual 0.5% probability of emitting two photons per pulse. The photonics states are generated in the desired spatio-temporal mode with a high 60% efficiency. Using homodyne-tomography measurements, we determine the density matrix leading to the Wigner functions. In agreement with theoretical predictions, these functions are quadrature-squeezed for small qubit rotation angles θ, and develop a negative region when θ approaches π and the one-photon component becomes dominant.

We will also investigate the limits of the perfect superatom model. Indeed, the two-level behaviour of our atomic ensemble relies on the strong interactions betweens Rydberg-state atoms. We will introduce a new model describing efficiently an imperfect Rydberg blockade in a small atomic cloud. In order to test this model, we perform coherent Rabi oscillations on our "superatom" for three Rydberg states $n = 80, 95, 109$ and measure Rydberg residual population as well as photon number extracted from the cavity of differents qubit rotation angle. For high Rydberg 109 state our model is in good agreement with the experiment. The model's accuracy decreases with lower Rydberg states and long exciation duration where higher-order effects become more pronounced.

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Cavity-enhanced atomic magnetometer for micro-bio-magnetic measurements

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In optically pumped magnetometers (OPMs), an optical probe detects coherent precession of an atomic ensemble due to a magnetic field. Commonly employed optical probes employ optical polarization rotation or optical absorption. Here we study a probe based on optical phase shifts. We demonstrate continuous Pound-Drever-Hall (PDH) nondestructive monitoring of the electron spin polarization of an atomic vapor in a microfabricated vapor cell within an optical planar resonator by measuring the resulting line shift of a circularly polarized cavity mode [1]. The method appears well-suited to improving the effective optical path in micro-fabricated atomic vapor cells, analogous to what has been done with multi-pass geometries in macroscopic cells. The signal enhancement will be proportional to the cavity finesse, that in our case, $\mathcal{F} \approx 18$ (for a detuning of $2\pi \times 115\,\mathrm{MHz}$).

We apply this PDH technique to monitor Larmor precession by recording train of free induction decay (FID) signals for magnetometry. We describe the application of this FID OPM to detection of signals from magnetotactic bacteria.

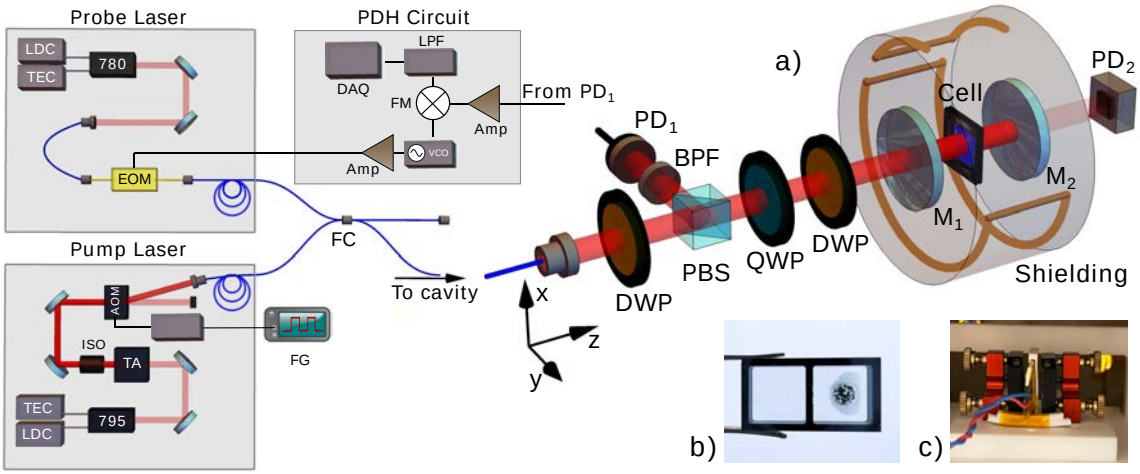

Figure 1: Experimental setup for cavity-based detection of atomic polarization. (b) MEMS cell. Picture of the two-chamber microfabricated vapor cell after activation by UV decomposition of rubidium azide $^{87}RbN_3$. The physics (reservoir) chamber is in the left (right) portion of the cell. (c) Cavity and cell. Picture of the probe resonant cavity consisting of two planar mirrors surrounding the MEMS cell, which is heated and thermally insulated.

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Exploring noise-induced Fano interference in a hot vapor atomic gas

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In a multi-level quantum system Fano coherences stand for the formation of quantum coherences due to the interaction with the continuum of modes characterizing an incoherent process [1, 2]. When the incoherent source vanishes, Fano coherences tend to disappear. The formation of quantum interference between internal states generated by "noisy" conditions has particular significance for systems in contact with thermal reservoirs, as photovoltaic devices, photodetectors or quantum heat engines. As suggested by [3, 4], their performance could see improvements. We propose a V-type three-level quantum system realized in the hyperfine structure of hot ^{87}Rb atoms, as depicted in Figure 1. The objective is the detection of spatial anisotropy in the fluorescence spectrum of the atomic system driven by an incoherent field, thereby confirming the existence of noise-induced Fano coherences, as explained by Dodin *et al.* in [5]. This will offer the first observation and new insights into quantum coherence phenomena arising from non-coherent excitation in a multi-level atomic system, potentially paving the way for the development of novel high-efficiency devices.

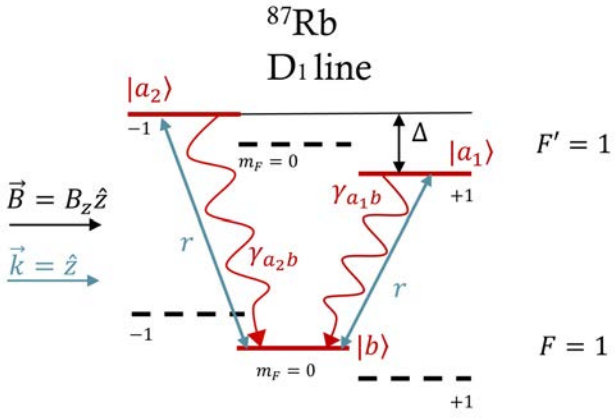

Figure 1: V-type three level system in the ^{87}Rb D_1 transition hyperfine structure. The system is driven by an incoherent source, with pumping rate r, close to the transition frequencies. Rates γ_{a_1b}, γ_{a_2b} are the decay rates. A uniform magnetic field $\vec{B} = B_z\hat{z}$ is applied along $\hat{z}$ axis.

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Rydberg excitation efficiency in nitric oxide using a three photon excitation scheme for a trace gas sensor

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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 [1, 2]. We showed in a proof–of–concept experiment the operation of a NO trace–gas sensor at ambient pressure [3] at a concentration of 10 ppb. At this point we are optimizing the efficiency and sensitivity of our experimental setup. We already resolved the hyperfine structure of the ground state transition $\mathrm{A}\,^2\Sigma^+ \leftarrow \mathrm{X}\,^2\Pi_{3/2}$[4].

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

$$nl(N^+)\ \mathrm{X}^+\,^1\Sigma^+ \leftarrow \mathrm{H}\,^2\Sigma^+ \leftarrow \mathrm{A}\,^2\Sigma^+ \leftarrow \mathrm{X}\,^2\Pi_{3/2} \quad ,$$

which are at about $226\,\mathrm{nm}$, $540\,\mathrm{nm}$ and $835\,\mathrm{nm}$, respectively.

We report on the collisional shift and line broadening of Rydberg states in nitric oxide (NO) with increasing density of a background gas at room temperature [5]. As a background gas we either use NO itself or nitrogen (N_2) and identify pressures for an optimal operation of our sensor.

We also show Stark shift measurements to investigate optimized electric fields for our NO detection.

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Two-photon double ionization of H_2 with sub-femtosecond laser pulses

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Monitoring electron dynamics in matter requires the use of coherent light sources that can offer attosecond resolution. For more than two decades, attosecond experiments have been mostly performed using table-top experimental set ups where trains of attosecond pulses are produced through high-harmonic generation (HHG). However, in the last years, free electron laser (FEL) facilities have sprout over the world, generating high brilliance and high intense pulses with a high frequency tunability, and more recently, even producing coherent attosecond pulses after the introduction of self-amplified spontaneous emission (SASE) schemes. The combination of these intense XUV sources with advanced detection devices that enable coincident measurements of all charged fragments enables a complete dynamical characterization of non-linear phenomena in the XUV and X-Ray regimes that remained experimentally unaccessible until now [1]. These technological progress thus call for accurate and reliable theoretical methods to unravel the role of nuclear motion and electron correlation in the excitation and ionization process. We here present a full dimensional solution for the two-photon double ionization of H_2 molecule. Very few theoretical works have addressed this problem due to difficulty and computational cost of achieving an accurate evaluation of the strong correlation between all fragments in the four-body Coulomb breakup, and only frozen-nuclei approaches have been employed until now [2]. In this work, we have implemented a new computational tool to describe, for the first time, the multiphoton double ionization of H2 including electronic and nuclear degrees of freedom at equal footing, i.e., working beyond the Born-Oppenheimer approximation [4]. We employ a numerical representation of the molecular wave function directly written in a basis set of FE-DVR (finite elements combined with a discrete variable representation), and apply an exterior complex scaling procedure to impose the appropriate many-body Coulomb boundary conditions [3]. We present accurate angle and energy differential two-photon double ionization yields. We first investigate the role of nuclear motion. We found significant energy displacements in the photoelectron spectra with respect to frozen nuclei. More interestingly, the correlated emission of the photoelectrons is strongly affected, leading to counterintuitive angularly resolved double ionization yields with respect to its atomic analog, which are due to novel interferences that arise from sequential two-photon absorption paths through different cationic states.

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Chiral coherent control of electronic population transfer with femtosecond pulses

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Enantioselective photochemistry relies on the ability to induce different electronic transitions in left and right handed versions (opposite enantiomers) of a chiral molecule using light. This is challenging because opposite enantiomers share the same energy spectrum and excitation with circularly polarized light is very weakly enantioselective. Highly enantioselective photochemistry is very attractive because it could provide a laser-based alternative to the usual chemical methods for enantiomeric purification and enantioselective synthesis. These are tasks of immense importance in the chemical industry, where the objective is to produce samples with only one of the two enantiomers starting from 50:50 mixtures. Great progress has been achieved recently in the context of coherent control over rotational excitations [1]. Extending such techniques to electronic excitations and shorter time scales is challenging but holds great promise as it could enable enantio-selective control on the femtosecond time scale in the liquid phase. Here we discuss how to tailor the polarization and the spectrum of the light to induce highly enantioselective population transfer between electronic states using intense femtosecond pulses. Our results are supported by an analytical model and ab-initio simulations, and take into account the molecular orientation distribution and the variation of the field across the sample [2].

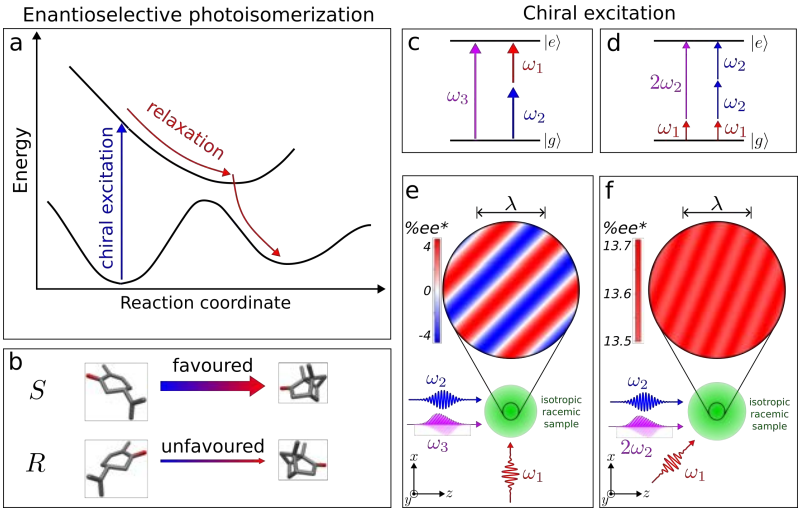

Figure 1: **a**. Photochemistry is triggered by electronic excitation, which often leads to chemical rearrangements (e.g. isomerization or dissociation). **b**. If the electronic excitation is driven by chiral light, the excitation becomes more likely in one of the two enantiomers. **c**. Enantioselective excitation can be achieved via coherent control. The 'microwave approach' [1] relies on 1-vs-2 photon interference. It leads to a rapid oscillation of the enantioselectivity across the interaction region (see **e**), hindering applications in the optical domain. **d**. Such oscillations can be avoided (see **f**) by careful design in a 2-vs-3 photon interference scheme.

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Phenomena of Quasi-1D Quantum Dipolar Droplets in Weak and Strong Interaction Regimes

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Confining the cloud of ultracold atoms in an elongated, quasi one dimensional trap has opened the possibility of investigating nonlinear phenomena such as matter-wave solitons and many-body effects like fermionization or (super)Tonks-Girardeau states. The plethora of intriguing results and experimental advancements holds promise for future applications in atomtronics.

Our theoretical research focuses on studying quasi-one-dimensional system, but with a dipolar gas. The interplay between the attractive dipolar and repulsive van der Waals interactions may lead to quantum self-bound states, as pointed out in [1]. In my group, through the application of many-body methods, hydrodynamic description, and mean-field techniques, we predict the emergence of one-dimensional quantum droplets within this system, from weak to strong interaction regimes [2].

These droplets show novel many-body effects and nonlinear phenomena. Within a dipolar quantum droplet, one may generate dark solitary wave with a steerable width, theoretically infinitely broad [3]. Intriguingly, a one-dimensional dipolar droplet, when subjected to a change in van der Waals interaction strength from repulsive to attractive, exhibits unexpected many-body behaviour. Instead of collapsing (which, intuitively, would be the expected scenario given all forces are attractive) or increased stability (as known due to the super Tonks-Girardeau effect), the droplet evaporates [4]. During the EGAS 55 conference, I would like to elucidate the origin of such droplets and their unexpected features. I will conclude with a discussion of the difficulties of the feasibility of creating these quasi-one-dimensional objects in real three-dimensional systems.

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Instabilities of superfluids in optical lattices under Floquet driving

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Ultracold atoms held in optical lattice potentials have emerged as promising candidates for quantum simulators and quantum computation. In particular, Floquet engineering, manipulating the system's properties by applying a periodic driving, plays a crucial role in generating artificial gauge fields and exotic topological phases. However, driving-induced heating and the growth of phonon modes limit its applications in interacting many-body systems. In this work we study the stability of a driven Bose-Hubbard model over a wide range of driving frequencies. At high frequencies the response of the system is chiefly governed by parametric resonances, while at low frequencies modulational instabilities, similar to those seen in static systems, become important. At intermediate driving frequencies an interesting competition between the two types of instabilities will occur. We experimentally confirm the presence of these instabilities, in both untilted [1] and tilted [2] lattices, and probe their properties. Our results allow us to predict stable and unstable parameter regions for the minimization of heating in future applications of Floquet engineering.

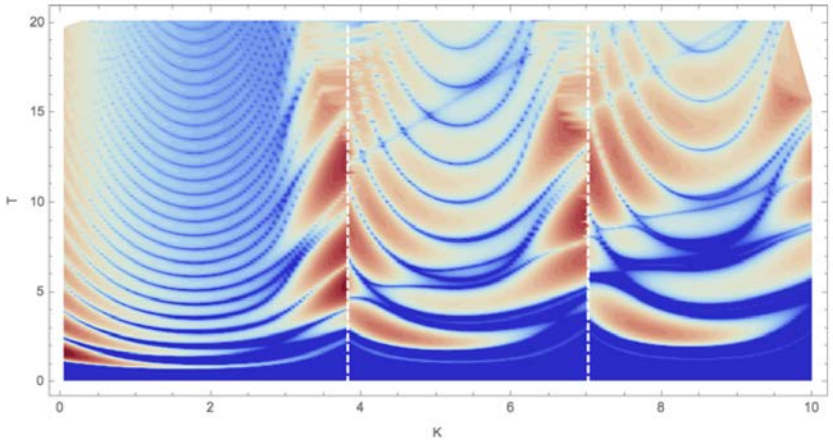

Figure 1: Stability of a tilted driven Bose-Hubbard model, as a function of the amplitude K and the period T of the driving. Blue regions are stable, while red areas are unstable.

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Ultrafast Rydberg experiments with ultracold atoms

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Rydberg atoms, with their giant electronic orbitals, exhibit dipole-dipole interaction reaching the GHz range at a distance of a micron, allowing ultrafast quantum operations. However, this has never been harnessed so far because of the stringent requirements on the fluctuation of the atom positions and the necessary excitation strength. Here, we introduce novel techniques to enter and explore this ultrafast Rydberg regime [1, 2].

I will introduce the *Rydberg timescale* to position the various limits and opportunities set by atomic physics properties of Rydberg orbits, as well as the technical challenges in reaching them with today's experimental tools. We will then look at how we excite Rydberg atoms as fast as physically possible ($\sim$ 10 picoseconds) by using techniques of pulsed lasers, non-linear optics and spectral optimization. With the atoms *instantaneously* transferred to the Rydberg states, we will discuss how fast they can interact with each other through long-range dipole-dipole interaction and I will show experiments displaying a coherent evolution in the nanosecond timescale. Finally, we will consider how the dipole-dipole interaction couples coherently the internal electronic Rydberg dynamics to the external motional degrees of freedom (position, momentum). I will show signatures of this effective "spin-motion" coupling with atoms trapped both in optical tweezers as well as in optical lattices. I will conclude with opportunities offered by quantum control of the motional states through motional squeezing or Floquet engineering, and the prospects for quantum simulation in this enlarged Hilbert space [3].

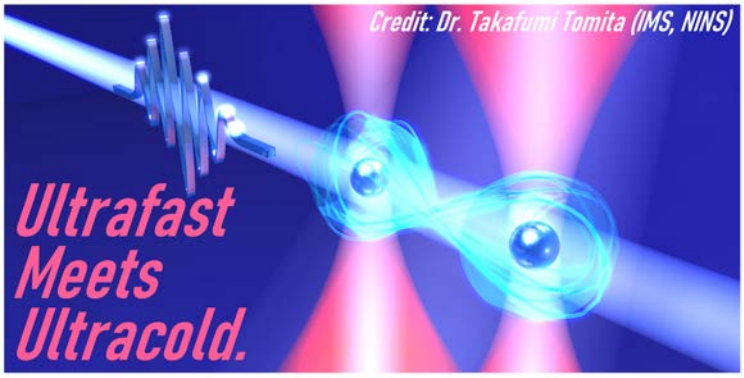

Figure 1: Artistic view of two trapped atoms in strong interaction after excitation by an ultrashort laser pulse.

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Direct laser cooling of Rydberg atoms with an isolated-core transition

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Whereas ground-state atoms and small molecules have already been laser cooled, Rydberg atoms have never been directly laser cooled. This is explained by the absence of a suitable cooling cycle for the Rydberg electron. Instead, we theoretically propose to laser cool the ion within the Rydberg electron orbit using the fact that the ion core is, to a good approximation, isolated from the Rydberg electron [1]. We illustrate our scheme with the Ca atom, using the $4s_{1/2} - 4p_{1/2}$ isolated-core transition to achieve cooling and the $3d_{3/2} - 4p_{1/2}$ one to close the cooling cycle.

When the ion core of an atom in a high Rydberg state is excited, its energy lies above the first ionization threshold. When the orbital angular momentum ℓ of the Rydberg electron is small, the atom typically undergoes autoionization (~ 0.01 to 0.1 ns) and decays much faster than the ion core (radiative lifetime ~ 10 ns). For sufficiently high ℓ values ($\ell \geq 10$), it is however possible to suppress autoionization far below the radiative lifetime of both the ion core and the Rydberg electron [2, 3, 4]. In this case, the lifetime of the states is extended to > 100 µs, which makes it possible to realize many isolated-ion-core cooling cycles.

To demonstrate the feasibility of our scheme, we theoretically calculate the energy-level structure of the states involved in the cooling cycle. Their number is increased and their energy split compared to the isolated ion due to the residual Coulomb interaction between the electrons of the ion core and the Rydberg electron. We examine population dynamics over the 200 states of the cooling cycle and demonstrate that an ion-core photon scattering rate of $\sim 10^7$ s^{-1} can be achieved. In the presence of a small magnetic field, this rate can be maintained over the radiative lifetime of the Rydberg atoms. We also discuss the effects of polarization on the population dynamics and compare them to the case of the isolated Ca^+ ion. Our direct Rydberg-atom laser cooling scheme offers the possibility to manipulate Rydberg atoms without significantly perturbing the Rydberg electron and paves the way to exploring the properties of cold Rydberg gases as a function of temperature.

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Rydberg atomic polarimetry and electrometry of THz fields

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RF field sensing based on Rydberg-excited atoms in vapour cells has received immense interest over the past decade [1]. By probing the Rydberg atomic medium optically through electromagnetically-induced transparency (EIT), an RF electric field matching the transition between two Rydberg states reveals itself as an Autler-Townes splitting of the EIT signal. We have previously capitalized on this effect to implement an optical antenna for communication [2] and a standalone vapour cell transducer for distant field sensing [3].
Here we explore polarization spectroscopy of a linearly polarized THz field. We recently established $S \leftrightarrow P$ Rydberg transitions as ideally suited for polarization-insensitive electrometry [4]: when rotating the RF field polarization, the split EIT spectrum remains invariant. In contrast, the use of $D_{3/2} \leftrightarrow P_{1/2}$ and $D_{5/2} \leftrightarrow P_{1/2}$ Rydberg transitions yields polarization imprints on the EIT signal. Moreover, these two cases exhibit a compelling complementarity, where, for a resonant EIT coupling field ($\Delta_C = 0$), the detected probe fields will oscillate out of phase when the THz polarization is scanned. This is akin to the outputs of the two ports of a polarization beam splitter and as such our scheme implements a high accuracy balanced THz polarimeter.

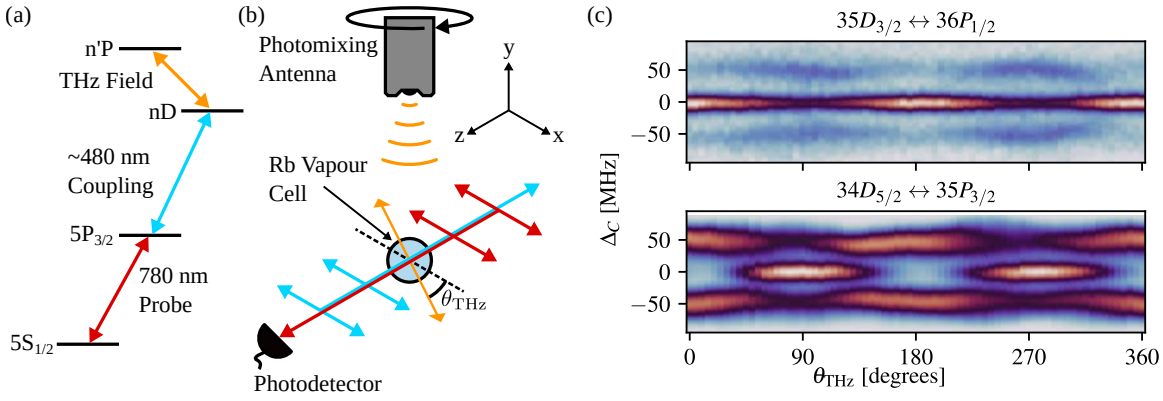

Figure 1: (a) ^{87}Rb EIT scheme for sensing a THz field. (b) Schematic experimental setup. (c) Transmitted 780 nm probe light in parameter space spanned by the 480 nm coupling laser detuning Δ_C and the polarization angle θ_{THz} of a THz field resonant with the Rydberg transitions $D_{3/2} \leftrightarrow P_{1/2}$ (top) and $D_{5/2} \leftrightarrow P_{1/2}$ (bottom).

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A new frontier in fundamental physics: precision spectroscopy of H_2^+

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Molecular hydrogen ions (MHIs) represent a class of bound quantum systems with significant potential for advancing our knowledge in multiple scientific domains, including the determination of fundamental constants, test of quantum physics, and the search for new interparticle forces. Furthermore, the comparison of transitions in MHIs and their antimatter counterparts provides an opportunity for novel tests of CPT invariance [1].

Among the various isotopologues of MHIs, heteronuclear HD^+ has been a focus of investigation in recent years, yielding significant data on its rovibrational transition frequencies as well as spin frequencies [2, 3, 4, 5]. In particular, our measurements of two rovibrational transitions provide data on the spin structure consistent with the most precise *ab initio* calculation [4, 5].

Expanding the scope of research to include other isotopologues of MHIs is crucial [6], with homonuclear H_2^+ being a valuable choice. However, spectroscopic studies of H_2^+ have historically faced difficulties because of lack of electric-dipole transitions, necessitating the development of alternative spectroscopic approaches. These challenges have prevented the realization of laser spectroscopy of H_2^+ until recently.

We have now succeeded in measuring a rovibrational electric-quadrupole (E2) transition in H_2^+ [7]. While the spectral lines exhibited Doppler broadening, in an additional study we demonstrated the feasibility of Doppler-free E2 spectroscopy, using HD^+ as a test molecule. We achieved unprecedented line resolution of 2.6×10^{12}, improving on a previous demonstration by six orders of magnitude [8].

A characterization of Doppler-free transitions in H_2^+ at metrological level would be a milestone, as it would lead to a spectroscopically determined electron-proton mass ratio. Therefore, our current efforts are focused on implementing Doppler-free vibrational spectroscopy of H_2^+. We have observed first Doppler-free signals, and will present up-to-date results at the meeting.

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High-Precision Measurements of Single Ions in the ALPHATRAP Penning Trap Setup

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At ALPHATRAP [1], we can inject externally produced ions form various sources into the cryogenic Penning trap setup and confine them for several months. Owing to the simple structure of hydrogen-like ions and molecular hydrogen ions (MHI) they allow precise theoretical predictions and are thus excellent systems for tests of fundamental physics. Our setup allows for high precision spectroscopic measurements on single ions, utilizing the continuous Stern-Gerlach effect (CSGE) for state detection [2]. With the determination of the g factor of the bound electon of hydrogen-like tin ($^{118}Sn^{49+}$), we have probed QED in the extreme electric field of the nucleus of 10^{17} V/m.
Moreover, we have nondestructively and unambiguously determined and manipulated the hyperfine substate within the rovibrational ground state of a single MHI, for the first time. This enabled us to perform high-precision microwave spectroscopy of the hyperfine structure (HFS) in the rovibrational ground-state of a single HD^+ ion and to determine the first experimental value of the bound-electron g factor of HD^+, to 0.1 ppb fractional uncertainty. This is an important parameter for unambiguous state determination of excited states of MHI for single-ion rovibrational spectroscopy, via each states unique electron-spin-flip frequency coupled with the CSGE [3]. Further, we have determined the spin-spin scalar interaction constants (E_4, E_5) to sub-100 Hz precision. These can be compared to ab-initio HFS theory which enters in the determination of a fundamental constant, the proton-electron mass ratio $m_\mathrm{p}/m_\mathrm{e}$ by rovibrational spectroscopy. Some previous data has shown unresolved deviations to this theory [4]. We are currently extending our methods to rovibrational spectroscopy of single MHI at infrared wavelengths, opening possibilities for CPT tests comparing H_2^+ and its antimatter equivalent, $\overline{H_2^-}$ [3].
I will present an overview of our setup and recent measurement results, focusing on the HFS of HD^+ and first steps towards rovibrational laser spectroscopy.

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From Doppler to quantum mass spectroscopy in a Penning trap

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The Penning trap is the prominent platform to perform motional-frequency measurements to deliver precise and accurate cyclotron-frequency measurements of many atomic/molecular ions and charged (anti)particles for many topics in fundamental Physics (see e.g. [1, 2, 3]). In the spirit of enhancing such precision and accuracy by means of Doppler cooling, the use of the laser-cooling transition together with photon-imaging and photon-counting units as detector increases the sensitivity [4, 5]. Since this type of cooling/readout can be only directly performed on a few ion species, they need to be the coolant and the detector of any target (charged) particle. An unbalanced two-ion crystal is formed, which does not prevent in the Doppler limit the perturbing effect of the Coulomb interaction on the motional-mode frequency measurements in a Penning trap.

At the University of Granada, we have built a platform based on a 7-T Penning trap [6, 7], recently upgraded with a cryogen-free magnet, with the first motivation of improving sensitivity in Penning-trap cyclotron-frequency measurements. We focus on the crystal $^{232}Th^{+}$-$^{40}Ca^{+}$, motivated by our medium-term goal of addressing $^{229}Th^{3+}$ proposed for the realization of a nuclear clock based on an isomeric-to-ground state transition in its nucleus below 10 eV [8]. After cooling all motional modes to the ground state, a quantum-based protocol can be utilized to probe each of the modes at the single phonon level [9]. In this contribution we will present the status of the laser-based Penning-trap mass spectroscopy experiments in Granada, including a comparison of the performance of the technique in the Doppler limit with the quantum regime. Since there is no limitation regardless the mass or charge of the target particle, other applications in Physics will be presented.

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Frequency metrology with antimatter

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According to the fundamental symmetries that underpin the Standard Model, both matter and antimatter should have been produced in equal quantities at the Big Bang. The absence of antimatter in our Universe as we observe it today, strongly motivates direct matter-antimatter comparisons, where any observed difference would lead to new physics. The Antihydrogen Laser Physics Apparatus (ALPHA) collaboration at CERN produces and traps antihydrogen atoms by combining antiproton and positron plasmas, which are subsequently used for precise studies. Recent progress includes the accumulation of thousands of atoms, direct laser cooling of the antihydrogen sample [1] and the first observation of the motion of antihydrogen in a gravitational field [2].

Laser spectroscopy of antihydrogen has already resulted in a test of CPT symmetry to a relative precision of 2×10^{-12} [4]. In hydrogen however, the same spectral feature, the 1S-2S transition, has been determined up to a precision of 4×10^{-15} [5]. To enable matter-antimatter comparisons at that level, we have implemented a Cs fountain clock in collaboration with NPL [3]. The fountain acts as a local absolute frequency reference and is used to steer an active hydrogen maser in the same laboratory. In addition to comparing the frequency of the maser with our fountain, we also cross-check against national metrology labs via satellite frequency transfers. A frequency comb and a stabilized fiber link, as well as two ultra-low expansion cavities, then allow for accurate determination of the laser frequency that is experienced by the antihydrogen atoms.

I will present recent progress and the current status towards a more precise comparison of the 1S2S transition in hydrogen and antihydrogen. I will also detail how we plan to access fundamental quantities, such as the Rydberg constant in an antimatter system and the antiproton radius, by carrying out laser spectroscopy on higher-lying excited states in antihydrogen.

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Sympathetic cooling of a Be^+ ion by a Coulomb crystal of $^{88}\mathrm{Sr}^+$ ions: a test bed for taming antimatter ions (GBAR)

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The GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment installed on the antiproton decelerator ring -AD- at CERN takes up the proposal by J. Walz and Th. Hänsch [2] to study the free fall of a antihydrogen atom prepared at rest [1]. The experiment involves two trapped ions, one, the Be^+ ion is cooled by laser and the other, the $\overline{H}^+$ ion, is cooled by its interactions with the Be^+ ion (sympathetic cooling).

We present here a test-bed experiment designed to study the sympathetic cooling of a light ion by a cloud of laser-cooled heavy ions under mass-ratio conditions similar to those envisaged in the GBAR project (9/1). To this end, we are studying the pair $^{88}\mathrm{Sr}^+$ (the laser-cooled ion) and $^{9}\mathrm{Be}^+$ (the sympathetically-cooled ion). The choice of these two species has two advantages. First, the possibility of optically addressing the $^{9}\mathrm{Be}^+$ ion enables process diagnosis (kinetics and thermometry). And second, their mass ratio ($88/9 \approx 9.8$) is very close to that envisaged for GBAR.

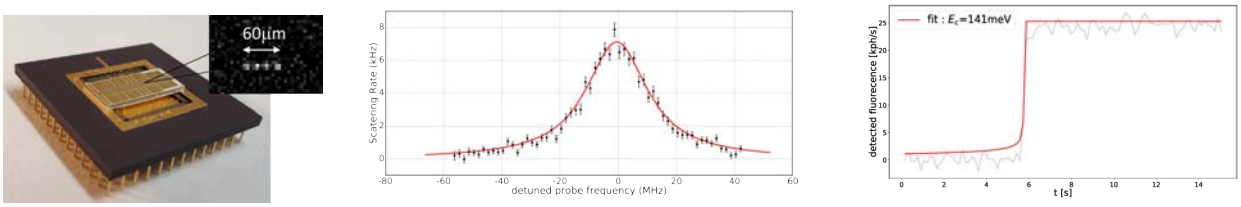

Figure 1: Left: Image of the trap. Center: fluorescence spectrum of a strontium ion. Right: fluorescence rise after launching a strontium ion in target trap, the fit gives the ion's initial kinetic energy.

We are developing a new setup with a 2-zone trap (see figure 1) to control the initial energy of a single Be^+ ion. A 313nm laser addresses the Be^+ ions. This will enable us to measure for the first time the capture dynamics of a light ion by a Coulomb crystal, and to follow its cooling over several decades (typically from 10000K to mK). We will compare these measurements with numerical simulations [3].

Initially, only Sr^+ ions were used to validate the trapping and cooling conditions, characterize the photon collection optics and test the transport protocols of a single ion from one trapping zone to another. A method for characterizing the initial energy of a Sr^+ ion on arrival in the target trap has been developed (via Doppler recooling, see the right plot on figure 1). We will present the status of our experiment with a Be^+ ion laser-coolded at 313 nm and transported with controlled kinetic energy to the second trapping zone, already loaded with a Sr^+ Coulomb crystal. Thermalization of the light ion via coulomb interactions will be investigated for different heavy-ion crystal temperatures, shapes and ion numbers.

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Investigation of the mercury intercombination line by means of comb-locked wavelength-modulated nonlinear spectroscopy

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Accurate measurements of isotope shifts are of paramount importance in atomic physics since they offer crucial insights into nuclear structure, atomic interactions, and, more generally, in fundamental Physics [1]. For heavy atoms, a direct method to investigate new physics scenarios (beyond the Standard Model) involves combining precise measurements of transition frequencies of different isotopes in the so-called King plots and looking for a possible King-plot nonlinearity [2].

In this study, we present absolute center frequency measurements of the $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1$ intercombination line of mercury atoms at 253.7 nm with a combined uncertainty at the level of 10 kHz. These measurements lead to a significant advancement in the current knowledge of the ^{200}Hg-^{202}Hg isotope shift for this spectral line. More specifically, we performed comb-locked saturated absorption spectroscopy in a 1-mm-long atomic vapour cell using a sensitive wavelength-modulation technique. The UV light is generated through an efficient nonlinear frequency-mixing scheme, which relies on a double stage of second harmonic generation processes within a pair of nonlinear crystals of an external cavity diode laser (ECDL) emitting at 1014.8 nm [3, 4, 5]. The near-infrared emission frequency is tightly locked to the nearest tooth of an optical frequency comb synthesizer referenced to a GPS-disciplined Rb clock. The UV radiation frequency is dithered by adding a modulation to the offset frequency between the near-IR ECDL and the nearest comb-tooth. Such a dither propagates throughout the frequency chain, while a fine-tuning of the comb repetition rate is performed, thus allowing accurate UV frequency scans across the intercombination line. This technical effort enabled us to observe a narrow comb-calibrated dispersion-like profile in coincidence with the Lamb dip. Following a thorough investigation of the AC Stark shift, we achieved a remarkable precision and accuracy in measuring the absolute line center frequencies for both ^{200}Hg and ^{202}Hg isotopes, namely 6.8×10^{-12} and 1.3×10^{-11} in relative terms, respectively. Consequently, we determined the ^{200}Hg-^{202}Hg isotope shift with enhanced precision and accuracy as compared to the past literature [6].

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Optical spectroscopy and inelastic collisions of the laser-cooling candidate anion C_2^-

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Cryo-cooled radiofrequency ion traps have become a widespread tool for spectroscopic and collisional studies of molecular and cluster ions at low temperatures. In particular multipole radiofrequency ion traps are well suited to cool translational and internal degrees of freedom of trapped molecular ions in a cryogenically cooled buffer gas [1, 2]. Negatively charged molecular ions have drawn a lot of attention, because a growing number of negative ions have been detected in different interstellar molecular clouds [3]. Here, recent work on the homonuclear molecular anion C_2^- will be presented. This anion has been proposed as a possible candidate for direct laser-cooling of negative ions [4], which may serve as a cooling agent for trapped antiprotons. We have carried out a precise spectroscopic characterization of a possible laser-cooling transition in C_2^- [5] in a cryogenic 16-pole wire trap [6]. Furthermore, we have measured the rate coefficient for vibrational state-changing collisions $v = 1 \rightarrow 0$ and compared them with quantum scattering calculations [7]. Using these vibrational quenching collisions allowed us to close the optical cycle and observe the fluorescence of a cloud of cold trapped C_2^- anions [7].

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False vacuum decay via bubble formation in ferromagnetic superfluids

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A classical system can have multiple equilibrium states at different energies; the absolute ground state is a stable configuration, while the other local energy minima are metastable. In a quantum field theory, quantum fluctuations can trigger the macroscopic tunneling of the field from a metastable state (the false vacuum) to the ground state (true vacuum) through the many-body energy barrier [1]. The decay of a false vacuum, which is thought to manifest via the nucleation of spatially localized bubbles of true vacuum, is a fascinating phenomena for a rich variety of systems, ranging from condensed matter [2] to cosmology [3]. Nevertheless, its experimental verification has been elusive so far, due to the extreme energy scales involved and the lack of tunable parameters. Here, I will present the first experimental evidence of false vacuum decay in a metastable ferromagnetic superfluid [4]. In this novel platform, realized with ultracold sodium atoms [5], the superfluid acts as the quantum field, and macroscopic tunneling events are observed through the spontaneous nucleation of spin bubbles. Our results find good agreement with numerical simulations and instanton theory, opening the way for the simulation of out-of-equilibrium phenomena in a highly controllable and tunable atomic system.

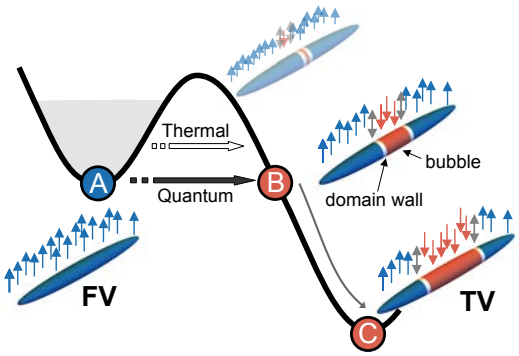

Figure 1: False vacuum decay process. Tunneling occurs from the false vacuum (A) to the resonant state (B), leading to bubble formation. Once formed, the bubble eventually expands into the true vacuum state (C).

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Heteronuclear quantum droplets under the microscope

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As predicted by D.Petrov [1], liquid-like quantum droplets may form in two-component bosonic mixtures due to the competition between the attractive mean-field energy and the repulsive Lee-Huang-Yang (LHY) correction coming from quantum fluctuations. So far quantum droplets have been realized in both homonuclear [2, 3] and heteronuclear [4, 5] mixtures by magnetically tuning the contact interactions. In the latter case, the droplet lifetime, which is limited by three-body losses, is prolonged [6] enabling the study of phenomena occurring on a time scale of tens of milliseconds.
Here, we report on the development of a custom microscope for the high-resolution imaging of a ^{41}K-^{87}Rb mixture. The objective consists in a commercial aspheric lens plus a meniscus lens and has a diffraction-limited resolution of about 1 μm, allowing to resolve micrometer-sized samples, such as quantum droplets. We exploit this optical system to track the dynamical evolution of a strongly attractive mixture in a horizontal optical waveguide. We prepare a non-interacting dual-species condensate in a cigar-shape trap and, then, we drive the system out-of-equilibrium through an interaction quench to the droplet phase, which excites a compression-extension mode. Finally, we switch off one of the trapping beam and we let the mixture to evolve in the presence of radial confinement alone. The in-situ density profiles unveil that the sample axially expands up to a critical value and then splits into two ore more smaller parts, which we identify as quantum droplets. This phenomenon is analogous to the break-up of a classic [8] or quantum liquid filament [7] into drops as a consequence of the surface tension, which tends to minimize the surface area.
Our results prove that this system is well suited for exploring the proprieties of quantum droplets and the dynamics of such quantum liquids. Finally, we discuss future extensions of our work which may include the study of non-trivial superfluid structures, like rings and shells, as well as exotic vortex states and rotating droplets.

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Control and scattering properties in dipolar spin mixtures

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Lanthanides, such as erbium and dysprosium, are emerging as valuable resources in quantum-gas science [1]. Among interesting properties, they are known for their large spin manifold in the ground state. To utilize these characteristics, precise control of the spin population and a thorough understanding of collision processes are needed.

Here, we demonstrate a novel method for manipulating the spin population by means of a laser tuned to a clock-like transition present in erbium at 1299nm [2]. By applying a sequence of Rabi-pulse pairs we can climb the ladder of Zeeman sublevels and prepare arbitrary superpositions of spin states. This allows us to record Feshbach resonance spectra of various spin mixtures to investigate spin-dependent on- and off-resonant scattering processes. Our results can be used to benchmark quantum scattering calculations, and to identify regions allowing to tune inter- and intraspecies contact interaction. Furthermore, the use of interference between inelastic and elastic loss channels - characterized by a Fano profile in the Feshbach spectra - enables us to create long-lived spin mixtures of bosonic erbium.

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A programmable hybrid system of ultracold molecules and Rydberg atoms

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Ultracold dipolar systems, like atoms excited to Rydberg states and polar molecules, hold great potential for quantum simulation and computation. Rydberg atoms offer strong, long-range interactions, facilitating the engineering of quantum entanglement and multi-qubit gates through the Rydberg blockade mechanism. Similarly, polar molecules exhibit long-range interactions but also possess numerous long-lived internal states. These states can be effectively coupled using microwave fields and can exhibit long coherence times for robust storage of quantum information [1]. Programmable arrays of optical tweezers have enabled flexible trapping of both these systems, creating the possibility of a hybrid system that combines the advantages of both platforms.

In this presentation, I will present our hybrid system consisting of ultracold RbCs molecules in their rovibrational ground state and Rb atoms trapped in species-specific optical tweezers. I will demonstrate how Rydberg blockade due to the charge-dipole interaction with a RbCs molecule [2] facilitates the detection of individual molecules. Furthermore, I will describe the toolbox of techniques we have developed for the control and readout of individually trapped polar molecules in optical tweezers [3]. Finally, I will highlight some recent results on the production of heteronuclear Rydberg molecules in separate optical tweezers and the observation of resonant dipole-dipole interactions between a Rydberg atom and a polar molecule. These results lay the foundation for future explorations of quantum computation and precision measurements utilising this hybrid platform.

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Isotopologue-selective laser cooling of barium monofluoride molecules

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We demonstrate laser cooling of barium monofluoride (BaF) molecules, which are highly sought after for precision measurement applications. We synthesize time-sequenced optical spectra that can be precisely tailored to the hyperfine structure of this previously uncooled molecular species. Optimization of the optical spectra allows us to realize strong Sisyphus laser cooling forces that can efficiently collimate a molecular beam. Moreover, by carefully choosing the transitions involved in the cooling, we also demonstrate the first isotopologue-selective laser cooling of molecules, selectively addressing both the ^{138}BaF and ^{136}BaF isotopologues in the same molecular beam. Our results are an important step towards slowing and trapping of BaF molecules, and will also be useful for cooling other molecular species with complex level structure.

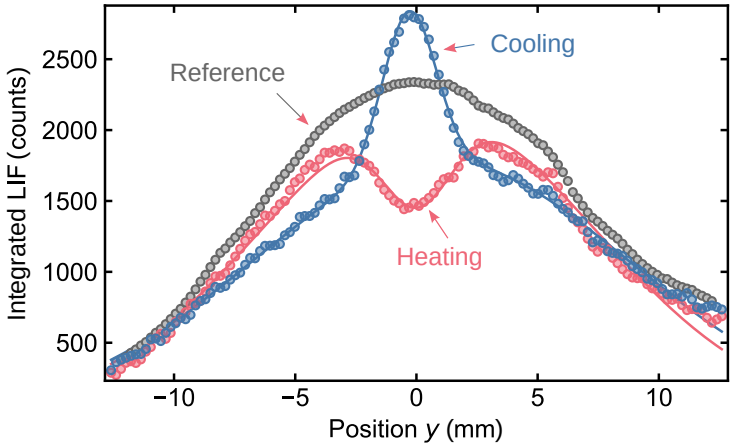

Figure 1: Laser-induced fluorescence (LIF) signal, showing cooling and heating of a BaF molecular beam.

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Ultracold coherent control of molecular collisions at a Förster resonance

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The advent of ground-state controlled ultracold dipolar molecules in dense gases has opened many exciting perspectives for the field of ultracold matter. When the molecules are dipolar, their extremely controllable properties have inspired many theoretical proposals for promising quantum applications, such as quantum simulation/information processes, quantum-controlled chemistry and test of fundamental laws.

Ultracold molecules can be used to probe chemical reactions with an unprecedented control at the quantum level. This was done recently with the chemical reaction KRb + KRb $\rightarrow$ K2 + Rb2 at ultracold temperatures. All the fragments of an ultracold chemical reaction, from reactants to products, including intermediate complexes, can now be observed [1]. The state-to-state rotational distribution of the products can be measured [2] and the rotational parities of the molecular products can be controlled with a magnetic field [3, 4].

We explore here the ideas of coherent control [5] applied to current experiments of ultracold chemical reactions. By using a microwave to prepare ultracold dipolar molecules in a quantum superposition of three stationary states (qutrit) and by using a static electric field to make collisional states degenerate, we predict that one can observe interferences in the rate coefficients of ultracold molecules. This work provides a realistic and concrete experimental set-up for current experiments to observe interferences and coherent control in ultracold collisions.

For more information, see Ref. [6]

Key Words : Ultracold Molecules, Coherent Control, Collisions, Quantum Dynamics

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Quantum jump photodetector for narrowband photon counting with a single atom

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Interfacing individual particles of light and matter is a foremost goal in quantum technologies. Quantum jumps, i.e. abrupt changes of quantum state, in atoms can be used to herald a photon absorption. In [1], we demonstrate a narrowband quantum jump photodetector (QJPD) to detect single-photons based on a single cold atom and quantify its experimental performance.

We introduce methodology, specific to the QJPD scenario, for determining the quantum efficiency (QE) and dark counts (DC) contributions in quantum jump photodetection. This system, similarly to CCD and CMOS detectors, has separated acquisition and readout time windows with distinct DC contributions. We demonstrate a QE of $2.9(2)\times10^{-3}$ (a record for a single atom in free space), a readout contribution of $1.8(1)\times10^{-2}$ counts per readout and a dark current of $9(20)\times10^{-3}$ cps, consistent with zero and limited by measurement statistics.

These DC are already competitive with any non-cryogenic detector. Several proven atomic and optical technologies could be applied to reach different wavelength ranges, narrower bandwidths, higher quantum efficiency, and lower dark counts. The QJPD technique may be interesting for a growing number of applications that require high sensitivity and strong background rejection through frequency discrimination, for example free-space quantum communication in daylight or space classical communications. The understanding of quantum jumps is also important in fundamental quantum optics to study the effect of different environments, or experimental apparatus, on a quantum system [2].

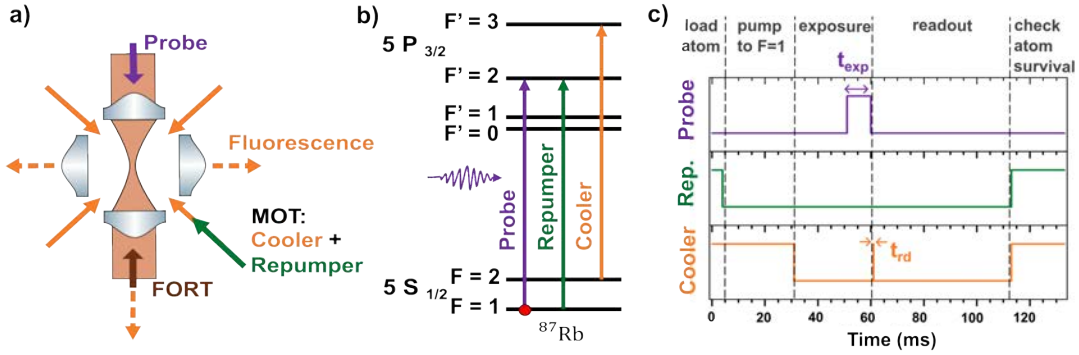

Figure 1: QJPD operation. a) Experimental set-up. b) Lambda system in which the ^{87}Rb QJPD operates. c) Experimental sequence: atom loading to far-off resonance trap (FORT), pumping to $F = 1$, exposing to probe for time t_{exp}, reading out with cooler light for t_{rd} and checking atom survival with cooler and repumper.

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Superoscillatory tweezer arrays for subwavelength trapping and manipulation of cold atoms.

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Spatial control of atoms with subwavelength accuracy is a crucial tool for quantum computing and quantum simulations. Using superoscillatory structured light we extend the recent work on single atom subwavelength trapping to few atoms superoscillatory tweezer arrays, where trap sizes and interdistances are dynamically tuned below diffraction limit.

Tweezer arrays of neutral atoms are a strong candidate for making a viable quantum computer. State-of-the art neutral atoms arrays use high numerical aperture lenses in vacuum to minimize the lattice parameter [1], effectively reducing the time for rearranging and increasing the qubit-qubit coupling, i.e. reducing the laser power and duration required for the various gates. It is thus important to continue looking for smaller lattice parameters to relief constraints on the laser system during the rearrangement and computing steps. This idea is also present in quantum simulation with neutral atoms, where one wishes to control the relative strength between tunneling and interaction in a generic Hamiltonian. Having a dynamically tunable lattice parameter for such a system is also very exciting and promise to reveal more of the phase diagram.

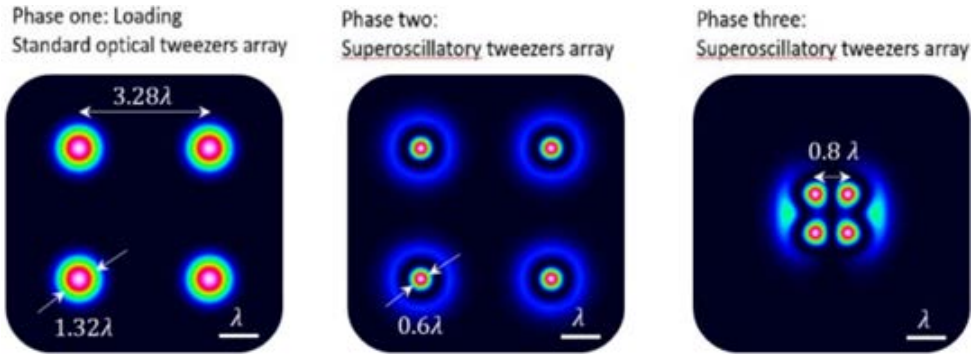

Figure 1: Three-step loading of four site tweezer array and subsequent transfer to subwavelength trap size and interdistances. Steps are quasi-adiabatically connected using spatial light modulators.

We have previously demonstrated the trapping of a single atom in a sub-wavelength superoscillatory tweezer [2]. Our next objective is to extend this concept to few atoms and demonstrate the loading and deterministic rearrangement of a superoscillatory tweezer array of a few sub-Doppler cooled thermal atoms. Fig.1 shows such loading sequence, where initially 4 atoms are loaded in a standard tweezer array then transferred in situ in the superoscillatory array and brought closer to each other at subwavelength distances. Another level of control is attainable by cooling the atoms to the fundamental state of the tweezer potential and control dynamically the tunneling between tweezers. This requires a precise control of the relative intensity and relative distance between individual sites to fulfil the resonant tunneling condition.

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High resolution spectroscopy of the atomic Sn^- system

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Tin (Sn) has the most stable isotopes of any element and marks a proton shell closure. As a part of the carbon group, the Sn anion is known to have an interesting resonant structure below the threshold of photodetachment which consists of a ^2D_J term. These ^2D_J states have the same parity as the anion ground state, meaning this transition will decay through forbidden *M1, E2* and higher order transitions. The energies of these bound states in the negative ion have already been investigated, but their lifetimes remained unmeasured [1].

Using a cryogenic ion-beam storage ring, DESIREE [2], we measured lifetimes of the $Sn^-(^2D_{3/2,5/2})$ states and the storage time of the anion. We first depleted both excited states, selectively excited to the $^2D_{5/2}$ state, and then probed this state again to detect the remaining neutral atoms. The method allowed us to precisely measure the lifetime of the $^2D_{5/2}$ state, and to determine that this was indeed the longer lived of the two states. We also were able to confirm the long-lived state by waiting to measure five lifetimes of the short lived state after the ion injection to ensure only the long-lived state was being probed.

Additionally, we were interested in measuring the isotope shift in the stable Sn isotopes. For negative ions, this can be accomplished by measuring the shift in the electron affinity value, e.g. [3]. However, we wanted to make use of the Sn^- resonant structure to investigate a high resolution method. The first measurements were highly successful as we were able to determine that the $^4S_{3/2} \rightarrow {}^2D_{5/2}$ transition was strong enough to detect. From this, we measured a preliminary isotope shift across $^{116-124}$Sn and resolved the hyperfine structure of the odd isotopes.

In this experiment, we were able to develop a new spectroscopy method to measure the lifetimes of bound states in negative ions, and to understand the feasibility of using the $^4S_{3/2} \rightarrow {}^2D_{5/2}$ transition in the Sn anion. In the future, we will have a follow up experiment where we will measure the isotope shift in the negative ion transition more precisely by measuring the wavelength using saturated absorption spectroscopy instead of relying on the internal mechanisms of the transition laser.

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Experimental demonstration of the coupling of trapped ions to a nano-wire

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Laser-cooled ions confined in strong electromagnetic fields are a well-established tool for atomic and molecular physics or quantum optics [1]. Their precisely controlled motional and internal states are advantageously used to probe and control bigger systems such as molecules [2] for which the capabilities of similar laser manipulations are very limited. The coupling of laser-cooled species with macroscopic systems such as nano-mechanical oscillators would unlock new unique manipulation techniques and diagnostic tools [3, 5]. Recently, we have reported the experimental demonstration of the coupling of $^{40}Ca^{+}$ ions with a charged Ag_2Ga nano-wire [4] (Fig. 1). Considering a single-point charge approximation and a monochromatic drive frequency for the nano-wire, an analytical model for the coupling between the $^{40}Ca^{+}$ ion and the nano-wire has been derived and has proved to be in good accordance with the first experimental results. This experimental demonstration is a first step towards the creation of more sophisticated ion–nano-wire couplings such as inducing coherent states of motion or the probing and control of the states of an ion and a nano-wire [5].

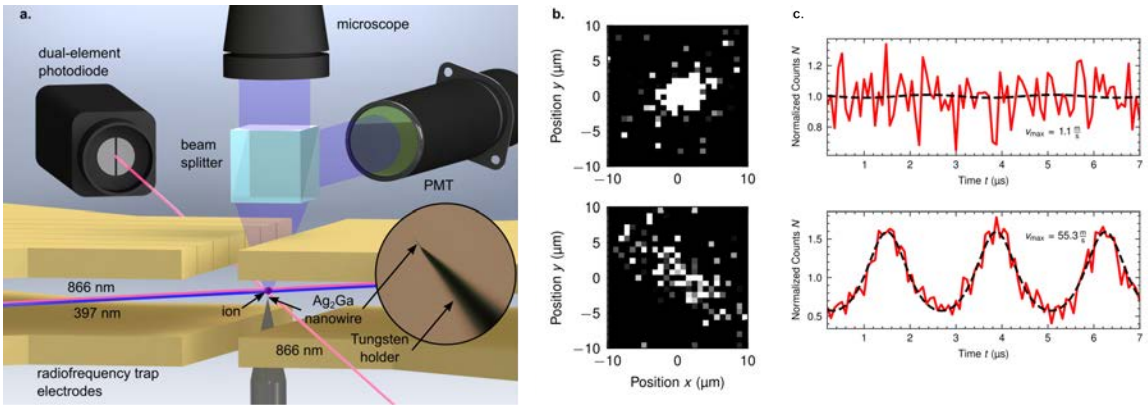

Figure 1: The ion–nano-wire hybrid system. **a.** Schematic of the experimental setup. The nano-wire is positioned close to the trapped ions in a miniaturised trap made of four wafers separated by 400 µm. **b.** Fluorescence image of a single ion without nano-wire drive (top) and with nano-wire drive (bottom). **c.** Histogram of arrival times of fluorescence photons correlated with the periodic drive signal of the nano-wire (2.37 µs period) : far off-resonant (top) and under near-resonant (bottom) motional excitation by the mechanical oscillator.

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Monday's Posters Abstracts

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PM 3 Grigory Astrakharchik, *Superfluid fraction of interacting bosonic gases*

PM 4 Dimitar Bakalov, *Hyperfine structure of the ground state of the molecular ion HD^+ in strong magnetic field*

PM 5 Ticijana Ban, *Absolute frequency measurement of the $^1P_1$ - $^1D_2$ transition in strontium*

PM 6 Clélia Bastelica, *Monochromatic source of ions and electrons for nanosciences*

PM 7 Bogdan Bednarski, *Cavity-enhanced spectroscopy of H_2 in a deep cryogenic regime*

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PM 47 Jordi Pera, *Interaction effects on the itinerant ferromagnetism phase transition*

PM 48 Michał Piłat, *Calculation of electron scattering lengths on Ar, Kr, Xe, Rn and Og atoms*

PM 49 Mariusz Piwinski, *Negative ion production for experiments with antiprotonic atoms*

PM 50 Rachel Poulose, *Mutual neutralization with manipulated initial quantum level distributions*

PM 51 Laurence Pruvost, *The orbital angular momentum of the photon and quantum interplay with atoms*

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PM 53 Fatima Rahmouni, *Towards a High Duty Cycle Transportable 171Yb Lattice Clock*

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PM 57 Henning Schmidt, *Atomic and molecular ion studies in the cryogenic ion-beam storage-ring facility, DESIREE*

PM 58 Ananya Sitaram, *Towards continuous superradiance for active optical clocks*

PM 59 Masanori Tachikawa, *Quantum Monte Carlo study on positron binding to atomic anion dimers*

PM 60 Hristo Tonchev, *Robustness of Grover's algorithm with multi-phase matching*

PM 61 Leandra Vranjes Markic, *Squeezed Bose-Bose droplets: binding, structure and vortices*

PM 62 Omar Zaidi, *Electron impact double ionization of krypton*

Supersolid-formation-time shortcut and excitation reduction by manipulating the dynamical instability

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Supersolids are a phase of matter exhibiting both superfluidity and a periodic density modulation typical of crystals. When formed via quantum phase transition from a superfluid, they require a formation time before their density pattern develops. Protocols and schemes are proposed for experimental applications, building on earlier descriptions of the role roton instability plays in the supersolid formation process and the associated formation time. In particular, two protocols are put forward to shorten the formation time and lessen the excitation produced when crossing the phase transition. As a case study of the impact that mechanical fluctuations (noise) can have on the phase transition when conducting an experiment, the impact of a mechanical kick before the transition is also investigated. The proposed schemes achieve a shortening of the formation process for comparable levels of excitation, in the framework of extended Gross-Pitaevskii theory.

Although the presented system is a dipolar BEC capable of sustaining dipolar supersolid, the requirements for the proposals to be useful are far more general and could as well be implemented on other systems featuring Modulation Instability, such as two component Bose mixtures transitioning from the miscible to the inmiscible regime.

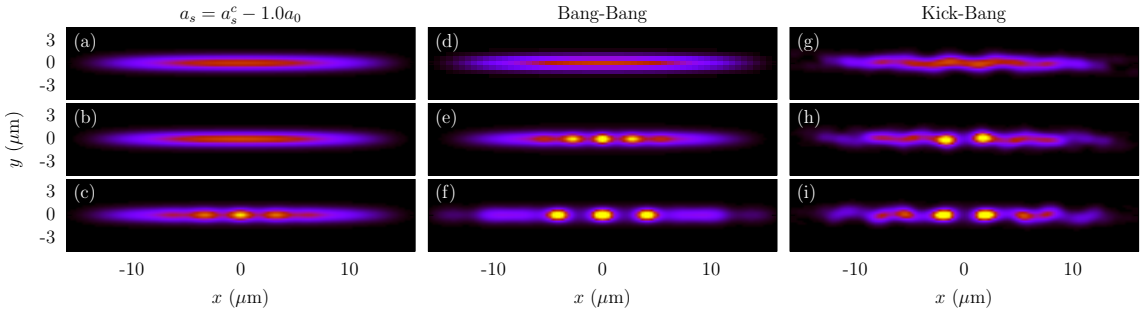

Figure 1: Evolution of the density distribution for a single quench from superfluid to supersolid and for the proposed optimization schemes (Bang Bang and Kick Bang). Each row shos density distributions at equal times.

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The effect of spin on the multiphoton photoelectron circular dichroism in iodomethylbutane

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We investigate the photoionization of chiral 1-Iodo-2-Methylbutane molecules with circularly polarized light. In particular, we are interested in spin-polarization (SP) [1] of photoelectrons and in the influence of SP on the Photoelectron Circular Dichroism (PECD, [2]). Although many results on PECD in the multiphoton ionization regime have been reported [3], the effect of spin on the multiphoton PECD has not yet been investigated. In this presentation, we aim to close this gap. To this end, we utilize the time-dependent single-center method which includes the spin-orbit interaction explicitly [4] and gives access to angular and spin resolution. Using this method we calculate the spectra and SP for the ionization from the three highest occupied orbitals (see Fig. 1) and compare them with the experimentally obtained results (see Fig. 2). Then we make sure, that the SP for R(-) and S(+) enantiomers must coincide if they are ionized by the laser with the same circular polarization. Finally, we predict, that the PECD may depend on the spin projection.

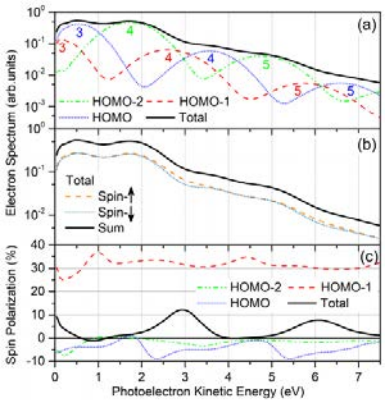

Figure 1: Theoretical calculations of photoelectron spectra and spin-polarization for 395 nm CPR pulse. The digits on the upper panel designate the number of absorbed photons.

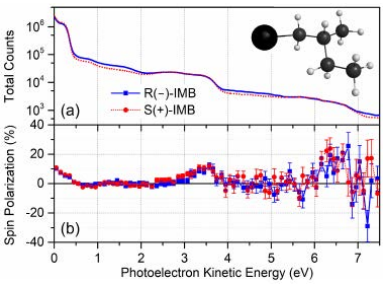

Figure 2: Photoelectron spectra and spin-polarization, measured for 395 nm CPR pulse.

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Superfluid fraction of interacting bosonic gases

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The superfluid fraction f of a quantum fluid is defined in terms of the response of the system to a weak and constant drag. Notably, Leggett long ago derived two simple expressions providing a rigorous upper bound and a heuristic lower bound for f. Here we study the superfluid fraction of bosonic gases in various two-dimensional potentials, such as regular optical lattices and disordered speckles, by solving the Gross-Pitaevskii equation and performing Diffusion Monte Carlo simulations. We show that under conditions relevant for most ultracold experiments the bounds proposed by Leggett provide a surprisingly narrow bracketing of the exact value of the superfluid fraction.

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Hyperfine structure of the ground state of the molecular ion HD^+ in strong magnetic field

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Molecular hydrogen ions (MHI) are three-body bound systems that allow for both high-precision spectroscopy and accurate theoretical description. Laser spectroscopy of ultracold trapped MHI is a perspective approach to improving the precision of the experimental values of fundamental physical constants, such as the electron-to-proton and proton-to-deuteron mass ratios [1, 2, 3, 4, 5], and to strengthening the limits on the time variability of these ratios [6, 7].
The hyperfine structure appears in the laser spectroscopy measurements and needs to be taken into account.

Measurements of the transition frequencies between Zeeman-split hyperfine levels in magnetic field, in particular, can provide experimental values of the hyperfine coupling coefficients and of the bound-electron g-factor, for comparison with theoretical predictions [8, 9]. Such measurements have been performed in the ALPHA-TRAP Penning trap in Heidelberg [10].

In order to compare the experimental values with theoretical predictions, it is necessary to evaluate the effects of the strong magnetic field $B = 4$ T on the hyperfine levels in the ground state of HD^+ of up to third order of perturbation theory. We find shifts on the order of 0.1 Hz.

The corrections to the energies are demonstrated to be reproducible by an effective spin-interaction Hamiltonian with proton-electron and deuteron-electron contact spin interaction coupling coefficients and bound-electron g-factor that depend on the magnetic field B; the explicit parametrization of the B-dependence is derived.

We acknowledge stimulating discussions with C.M. König, F. Heiße, S. Sturm.
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Absolute frequency measurement of the $^1P_1$ - $^1D_2$ transition in strontium

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Over the last decade, strontium has emerged as a key atomic species in a cutting-edge cold-atom-based quantum technologies. These include optical atomic clocks, which have achieved record precision, single-photon atomic interferometers, tweezer-based quantum simulators, and neutral-atom quantum computers. A deeper understanding of the electronic structure of atomic strontium, including its higher-lying electronic states, is essential for enhancing the performance of all the aforementioned applications. Nevertheless, spectroscopic measurements of optical transitions in strontium, as found in the literature, exhibit limited accuracy, highlighting the necessity for further measurements to enhance precision and accuracy.

We present the measurement of the absolute frequency of the $^1P_1$ - $^1D_2$ transition in atomic strontium. The strontium atomic beam is generated in an under-vacuum spectroscopy cell. We first populate the $^1P_1$ state using an on-resonance diode laser at ≈461 nm. Subsequently, we probe the $^1P_1$ - $^1D_2$ transition with a cw Ti:sapphire laser at ≈767 nm. The laser-induced fluorescence (LIF) is measured as a function of the Ti:sapphire laser frequency. Simultaneously with the LIF signal, we detected the beat signal of the Ti:sapphire laser and a nearest mode of the optical frequency comb (FC). FC is fully stabilized and referenced to a primary frequency standard thus providing the absolute frequency scale for LIF measurements.

The measured $^1P_1$ - $^1D_2$ transition frequency is 390599571.7 ± 0.4 MHz, with an accuracy that surpasses the previous measurement [1] by two orders of magnitude.

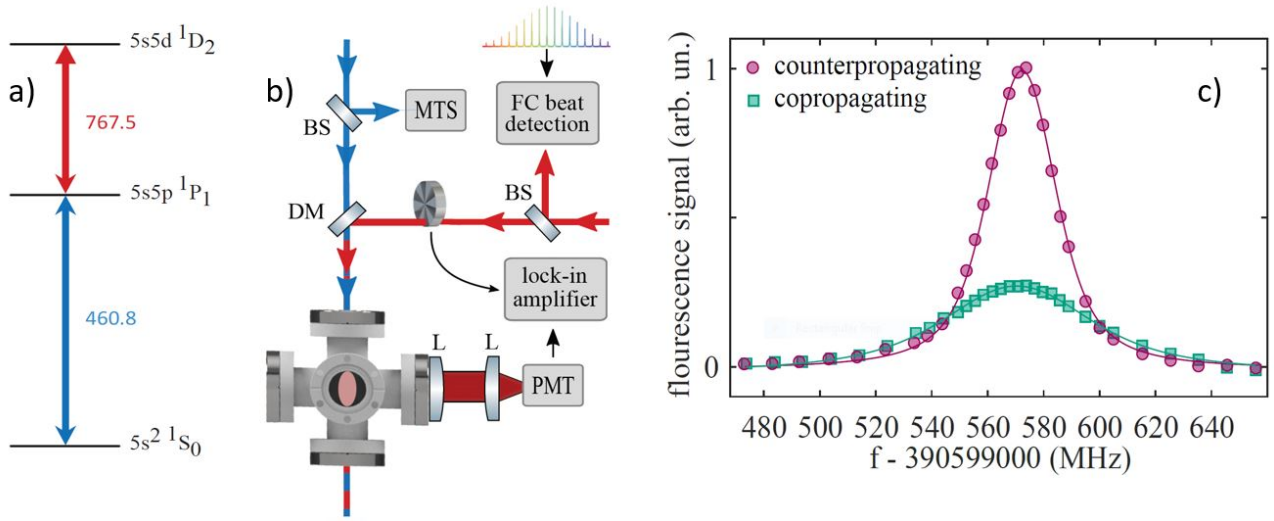

Figure 1: Energy levels (a), experimental setup (b), and LIF as a function of the Ti:sapphire laser frequency for counter-propagating (red) and co-propagating (green) laser geometries (c).

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Monochromatic source of ions and electrons for nanosciences

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Electron and ion beams have become indispensable tools in surface and material sciences, with the demand for ever-increasing resolutions. This project aims to develop a Focused Ion Beam (FIB), called FIBback, leveraging two innovative concepts:

- A correlated source of ions and electrons that demonstrates, among other applications, complete trajectory control of the ion using information from its correlated electron [1, 2].
- A FIB (called COldFIB) based on a cesium atoms beam collimated by laser, excited to a Rydberg state then ionized by field [3, 4].

We aim to enhance the resolution of ColdFIB by enabling the collection and detection of each electron created during the ionization process. To achieve this, we have developed several optical elements and a detector that will be incorporated into the FIB column. These additions will allow us to maintain the existing correlation between the electron on its detector and the ion on the sample, both coming from the same atom. The coincidence detection ion/electron provided information on both correlated particles which can be used to enhance beam properties. The beam resolution will be improved either by using the real-time trajectory control of each ion [1] or using ghost imaging [2]. This new FIB prototype will also provide a deterministic ion source.

With this innovative FIB, we aim to achieve nanometer-scale resolution at low energy, paving the way for high-resolution non-destructive imaging applications and deterministic implantation experiments.

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Cavity-enhanced spectroscopy of H_2 in a deep cryogenic regime

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We introduce, for the first time, a spectrometer based on a high-finesse optical resonator operating in a deep cryogenic regime, i. e., below 5 K. This system enables uniform cooling of the entire optical cavity, including the gas sample, the mirrors as well as the piezoelectric actuator (with tunability range exceeding 20 μm [1]). The setup is designed in a way that efficiently attenuates both external vibrations and those originating from the cryocooler itself, ensuring stable operation of the optical cavity.

The spectrometer, integrated with an optical parametric oscillator (OPO), facilitates the investigation of the fundamental band of H_2 in the range from 2.2 to 2.4 μm. We will demonstrate our first measurements of the rovibrational transition S(0) from 1-0 band in cold molecular hydrogen at 5 K in the Doppler-limited regime. Achieving accuracy at the level of 10^{-6}cm^1, our system allows for testing of the quantum electrodynamics (QED) corrections for H_2 at the fifth significant digit of the QED correction [2, 3]. By saturating the very weak quadrupole transitions in H_2 we expect to further enhance the accuracy by an order of magnitude. This is achievable thanks to the deep cryogenic regime of our cavity and high laser power provided by the OPO.

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Controlled dissipation for Rydberg atom experiments

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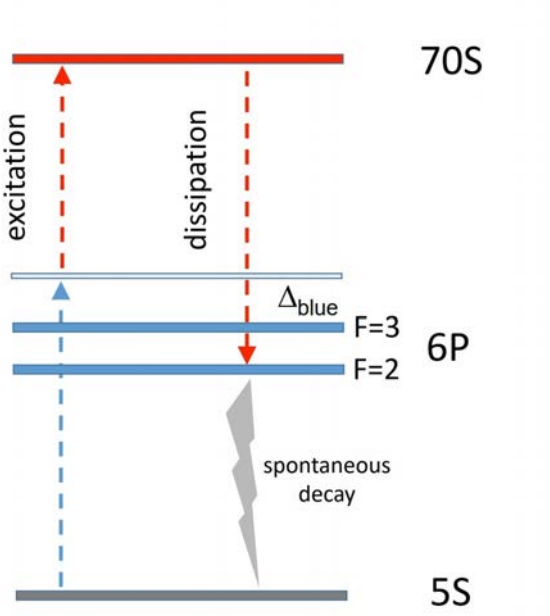
In ultracold Rydberg atoms studies in the context of quantum computation and simulation, dissipation and decoherence are usually detrimental and need to be minimized [1]. However, in the study of driven-dissipative systems exhibiting nonequilibrium phase transitions [2] or in the dissipative preparation of entangled states, the dissipation is a feature. In Rydberg atom experiments dissipation arises naturally from spontaneous decay to the ground state and black-body radiation induced transitions between Rydberg levels. Here, we demonstrate a simple technique for adding controlled dissipation (decay to the ground state) to Rydberg atom experiments [3]. Our approach involves exciting cold rubidium atoms trapped in a magneto-optical trap to 70-S Rydberg states while concurrently inducing forced dissipation. This dissipation is achieved by resonantly coupling the Rydberg state to a hyperfine level of the short-lived 6-P state as shown in the above figure. The resulting effective dissipation can be controlled in time during within a single experimental cycle.



Scheme for simultaneous excitation and controlled dissipation in rubidium Rydberg atoms. The 6P level is used both as an intermediate state for two-photon excitation (blue and red arrows on the left) and resonant depumping from the 70S Rydberg state (red arrow on the right).

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Electron dynamics in helium induced by multiphoton processes

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The widespread adoption of free electron lasers worldwide, capable of generating short and high-energy pulses, has greatly advanced the exploration of nonlinear phenomena in atoms. One such phenomenon, two-photon ionization, has revealed intriguing aspects of light-induced physical processes like asymmetric photoelectron emission [1, 2], providing insights into electron correlation. In this theoretical investigation, we explore the electron dynamics induced by multiphoton processes, with a focus on both single and double ionization. Our goal is to uncover deeper insights into the complexities of electron dynamics within the helium atom.

We first investigate double ionization processes in helium induced by two-color schemes. We analyze how the manipulation of double ionization yields is achieved by adjusting the time-delay between pulses of different colors. Furthermore, we showcase how this time-delay enables control and manipulation of angular electron emission, demonstrated through the variation of triple differential cross sections (TDCS) for different time-delays. In the second scenario, we explore the interference of multiphoton transitions occurring between odd triple harmonics of an IR pulse. Our theoretical investigation focuses on retrieving all the relevant relative and absolute phases induced by both the atomic potential and those introduced by the electromagnetic pulses, in order to design new strategies to access phases of different wave packets.

In both scenarios, we solve the time-dependent Schrödinger equation (TDSE) in full dimensionality, employing a numerical method that describes the wave function using a Finite Element Method and a Discrete Variable Representation (FM-DVR). [3, 4, 5] Time evolution of the TDSE is achieved using a Lanczos propagator, while the scattering function is extracted by extending the propagation to infinite time via Exterior Complex Scaling (ECS) of the electronic coordinates.

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EXPERIMENTAL OSCILLATOR STRENGTH FOR FORBIDEN LINE IN BARIUM ION

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Metastable levels are responsible for parity forbidden lines occurring in many low-density astrophysical plasmas, found in e.g gaseous nebulae, planetary nebulae, protostars, stellar chromospheres. Line ratios from forbidden lines are the reliable tool for diagnostics of temperatures and density of low-density astronomical objects.
We have applied the laser pump probe technique [1] on the DESIREE [2]. The lifetime of Ba II metastable state is measured with high precision , and the oscillator strengths for forbidden transition 5d $^2D_{3/2}$ => 6s $^2S_{1/2}$ can be evaluated with about 1% accuracy.

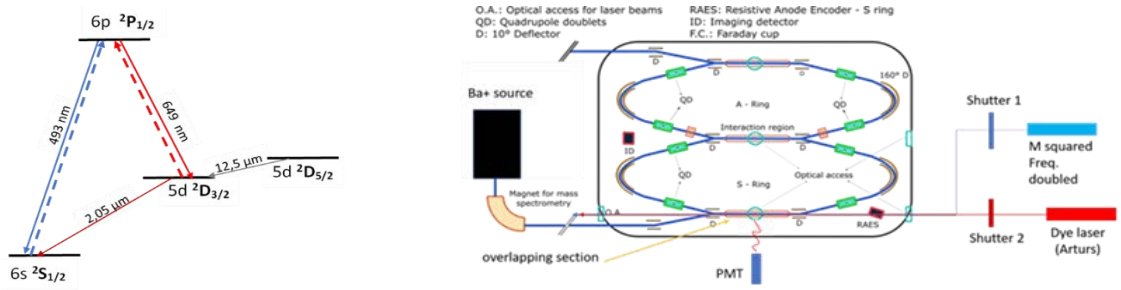

Figure: Barium ion energy levels and corresponding to the transitions used in the experiment (right) and the detection scheme used at DESIREE (left). Transitions are indicated with different arrows: 1) the laser excitation by dashed line and 2) solid for E1 transitions and 3) tiny for M2 transitions.
The transition wavelengths are written at the sides of corresponding arrows. Ba ion beam from the ion source are injected in experimental chamber inside the symmetric ring of DESIREE. Ba^+ beam is overlapped with two laser beams. First 493 nm laser is applied to empty the ground state all ions are pumped into metastable 5d $^2D_{3/2}$ state via 6p $^2P_{3/2}$ state.
Since there pressure and temperature are very in experimental chamber. The metastable are not quenched by collisions and stay in beam for hours [3] and they decay only via M2 transitions. The population of ions in 5d $^2D_{3/2}$ state is measured by probing it with 649 laser pulse and detecting the fluorescence light at different time between pump and probe pulses and evaluating the observed exponential curve. So lifetime is measured and directly from lifetime the oscillator strengths is evaluated , since only one M2 transition is possible.

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Quantum Monte Carlo based density functional for ultracold Bose gases

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The formation of liquid drops of Bose-Bose mixtures and dipolar atoms lead to denser systems than usual quantum gases. Even if these drops are ultradilute, they can show departure of universality in terms of the s-wave scattering length. Terms beyond the Lee-Huang-Yang in the perturbative series for bosons are not known, but probably depend on the effective range r_0 and the p-wave scattering length. We have used a combination of quantum Monte Carlo (QMC) methods and Density Functional Theory (DFT) to estimate first corrections to the universal terms. We observe measurable effects in the estimation of critical atom numbers in Bose-Bose mixtures [1, 2] and in dipolar systems [3] that lead to a better agreement with available experimental data.

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Effective three-body Interaction in Rabi-coupled two component Bose-Einstein condensates

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Mixtures of Bose-Einstein condensates offer situations with competing interactions where the usually dominant mean-field energy in weakly interacting systems can be reduced such that higher-order (for example beyond-mean-field) terms may play a dominant role in the equation of state. In this context, the case of two-component coupled Bose-Einstein condensates is specifically addressed. First, large attractive effective three-body interactions can be engineered with striking consequences [1] (see figure 1). Second, the beyond-mean field energy is precisely measured and is shown to be modified as compared to the uncoupled case [2]. It can be used to prepare a novel kind of quantum droplets. Recent improvements include stabilization of the magnetic field at the 3×10^{-6} level allowing precise control of the three-body interaction term, a new tool in quantum gases.

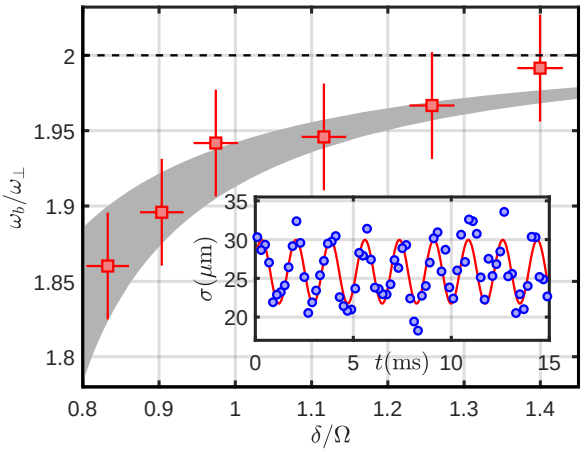

Figure 1: Radial breathing frequency of a condensate at Rabi frequency as a function of the detuning δ/Ω of the coherent coupling. The frequency downshift is an unambiguous signature of the three-body interaction term in the equation of state. The points correspond to the experimental data. The shaded area corresponds to the theoretical estimates. Inset: Example of radial breathing oscillations for $\delta/\Omega = 0.9$.

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Polarization effects in laser-assisted $(e, 2e)$ fast-electron-impact ionization of hydrogen

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The ionization of atoms by electron impact, referred to as the $(e, 2e)$ process, is one of the fundamental process in atomic physics and provides important information about the electronic structure of the atomic target and residual ion [1]. We consider the ionization of hydrogen by fast-electron-impact in the presence of a laser field with linear and circular polarization, at kinetic energies much larger than the atomic unit. We employ the first-order Born approximation in the electron-atom scattering potential taking into consideration the exchange effects [2]. We use a semiperturbative model [3] in which the interaction of the circularly polarized (CP) laser field with the incident and outgoing electrons is treated nonperturbatively by Gordon-Volkov wave functions, while the atom-laser interaction is treated by using first-order perturbation theory. We have derived a closed-form formula for the triple differential cross section (TDCS), valid for circular and linear polarizations [4]. We analyze the influence of the laser field polarization on the TDCS. An asymmetric non-coplanar scattering geometry is employed in which the polar and azimuthal angles of the scattered electron are fixed, while the emitted electron is detected at different angles. The numerical data for TDCS by a CP laser field are compared to those derived by a linearly polarized laser field, and differences are found in both magnitude and angular distributions of the TDCS.

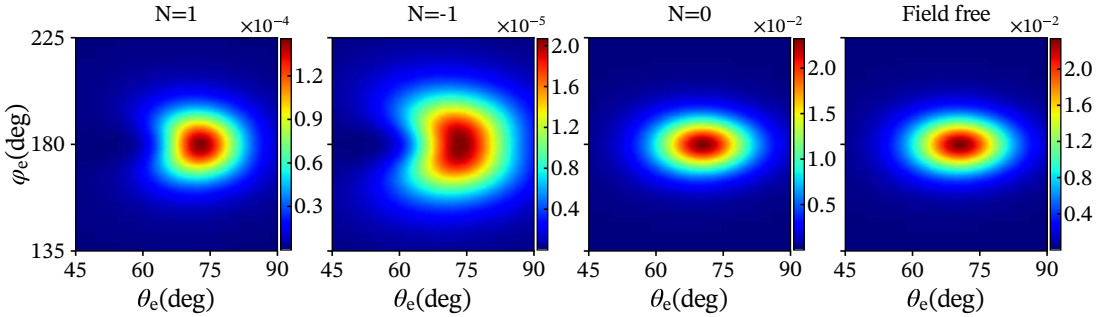

Figure 1: The TDCSs for the ionization of hydrogen by electron impact in the presence of CP a laser field, as a function of the polar and azimuthal angles of the ejected electron, θ_e and φ_e, at the photon energy $\omega = 4.65$ eV and laser intensity $I = 1$ TW/cm^2, for one-photon absorption $N = 1$, one photon emission $N = -1$, no photon exchange $N = 0$, as well the field-free results. The kinetic energies of the incident and ejected electrons are $E_i = 2$ keV and $E_e = 0.2$ keV, and the polar angle of the scattered electron is $\theta_f = 15^\circ$.

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Effective light-induced Hamiltonian for an atom with a large nuclear spin

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Ultra-cold fermionic atoms with two valence electrons have a unique internal state structure, as the nuclear spin is decoupled from the electronic degrees of freedom in the ground electronic state. The nuclear spin states are thus well isolated from the environment and can be used as a platform convenient for quantum computation and quantum simulation [1, 2]. A coupling with off-resonance light is an essential tool to selectively and coherently manipulate the nuclear spin states. Although light shifts in alkaline-earth-like atoms have been expressed in terms of the Clebsch-Gordan coefficients [3], these equations are complex to analyze and require numerical calculation.

In this work, we present a systematic derivation of the effective Hamiltonian for ultra-cold fermionic atoms with two valence electrons due to such an off-resonance light. We obtain compact expressions for the scalar, vector and tensor light shifts b_0, b_1 and b_2, taking into account both linear and quadratic contributions to the hyperfine splitting. The analysis has been carried out using the Green operator approach and solving the corresponding Dyson equation. Finally, we analyze different scenarios of light configurations which lead to the vector- and tensor-light shifts, as well as the pure spin-orbit coupling for the nuclear spin.

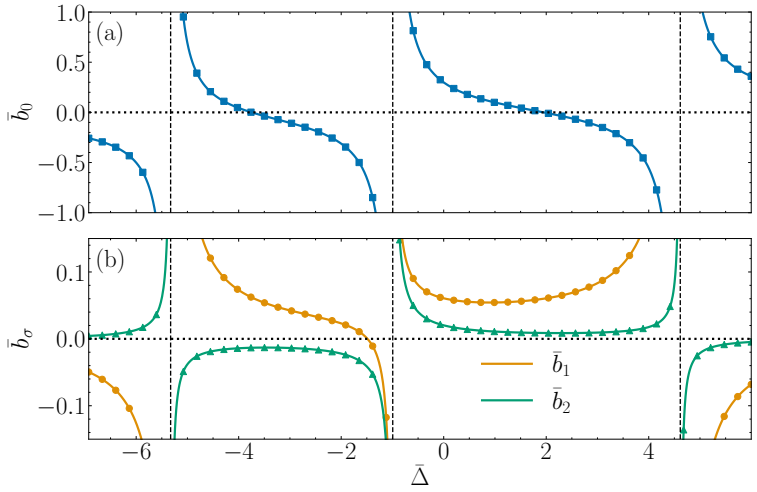

Figure 1: Dependence on the dimensionless detuning $\bar{\Delta} = \Delta/(\hbar A_{\mathrm{HF}})$ of (a) the dimensionless scalar coefficient $\bar{b}_0$, as well as (b) the vector $\bar{b}_1$ and tensor $\bar{b}_2$ coefficients entering the effective Hamiltonian. The values of nuclear spin $I = 9/2$ and quadratic shift $\gamma = 0.006$ are taken for ^{87}Sr atoms. Clebsch-Gordan calculations are marked by solid lines, while squares, circles and triangles represent our analytical results, respectively.

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Towards a Magneto Optical Trap of AlF molecules

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Polar molecules cooled to microkelvin temperatures promise new applications in quantum technology and chemistry. They can also be used as sensitive probes for new physics, and to study strongly correlated many-body quantum systems.

One way to cool molecules is to use lasers to cool and trap them in a magneto optical trap (MOT). However, compared to atomic MOTs, the number density of molecular MOTs is four to five orders of magnitude lower. This currently poses significant limitations on the applications of ultracold laser-cooled molecules.

Our group has identified Aluminum monofluoride (AlF) as an excellent candidate for direct laser cooling [1]. AlF is a chemically stable molecule that has a very strong transition in deep ultraviolet (DUV) near 227.5nm. The stability gives rise to a more intense molecular beam compared to the molecules that have been laser cooled so far [2]. In addition, we have demonstrated that a particularly high optical force can be exerted onto the AlF molecules. This results in a short slowing distance and a large capture velocity of the MOT [3]. The advantages we verified are essential to achieve a molecular MOT at a higher number density. In previous work, We performed detailed spectroscopy measurements on the states that are relevant to the cooling experiment of AlF [1], characterised the cycling transitions including the potential loss channels [3], and tested our MOT apparatus by loading a high density MOT of Cd atoms that have a strong transition near 229nm. Here we demonstrate our recent progress towards a MOT of AlF. We implemented different slowing schemes (Zeeman, chirped, and frequency-broadened slowing) on Cd atoms in DUV to test the experimental hardware and laser systems, and successfully slowed a beam of AlF molecules by chirped radiation pressure close to the predicted capture velocity of a MOT.

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Ionic polaron and bipolaron in a Bose gas

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Ultracold quantum many-body systems constitute an interesting research playground due to their wide range of applications, from precision measurements to transport phenomena in the field of condensed matter. One particular example are hybrid systems of atoms and ions, which are rapidly developing [1] and at ultralow temperature provide an ideal environment for the emergence of polarons. Namely, a quantum bath composed of bosonic atoms weakly coupled to an ion can be properly described by means of Bogoliubov theory. Nevertheless, this approach is no longer valid as soon as the strong coupling regime is taken into account, leading to an instability with an infinite number of bosons collapsing into the ion. Ion-atom systems feature long-range interactions which drive the system to form a many-body bound state with high density and large atom number [2]. In order to explore this physics and circumvent the bosons unstable behavior, based on [3], a variational approach is adopted. Employing a regularized potential that retains the correct long-distance behavior, we study the properties of interest in the formation of ionic Bose polaron and bipolaron, such as their energy, the number of bosons that takes part in the cloud formation, and the induced interactions which are tunable by the potential parameters.

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Optical control of divalent Rydberg atoms

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Neutral atoms are of interest for quantum computation and quantum simulation based on registers of cold atoms trapped in optical tweezers. Operations are performed thanks to the strong interactions between Rydberg states [1]. Once excited, the electron is no longer sensitive to the optical trap, which can lead to decoherence. On the other hand, divalent atoms still exhibit optical transitions from core electron transitions. This makes it possible to efficiently trap the ground state and the Rydberg state.

However, this optical manipulation is not without risk, since excitation of the ionic core of the Rydberg atom can lead to autoionization [2]. The total energy of the atom is then indeed above the ionization limit, and an exchange of energy between the two electrons releases an electron into the continuum.

We have studied autoionization as a function of the chosen Rydberg state [3] and of the wavelength used [4], and have been able to demonstrate that autoionization presents zeros enabling a trapping potential to be applied in the absence of autoionization. This will enable non-destructive optical trapping of divalent Rydberg atoms.

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Topological quantum dissipative phases with trapped ions

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We simulate topological dissipative phases in a one-dimensional chain of trapped ions with their vibrational degrees of freedom. First, we study non-reciprocity in a two-ion parametric dimer and then we analyze topological amplification in larger chains where Coulomb long-range couplings become apparent. The existence of topologically non-trivial phases in this non-Hermitian system leads to the presence of edge states that produce amplification being robust against disorder. The control of the parametric driving terms is achieved by taking advantage of state-of the art Floquet engineering techniques. We characterize the stability of the system and find stable topological amplifiers and two-mode Gaussian steady-states that can produce entanglement.

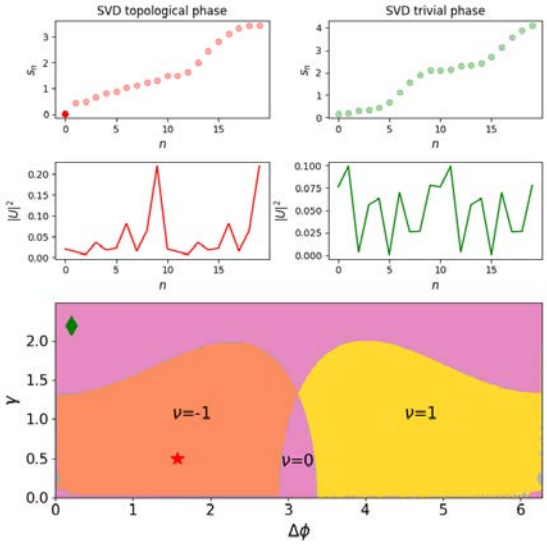

Figure 1: Topological phase diagram in the $\gamma - \Delta\phi$ parameter space. There are two similar non-trivial phases with winding numbers $\nu = \pm 1$ and a trivial phase with $\nu = 0$. The singular values and vectors of two points (red star and green diamond) of the topological phase diagram reveals the presence or absence of edge states and thus, amplification of input signals.

Quantum simulators are experimental devices with controllable quantum dynamics, designed to mimic a target complex quantum system or to explore intricate quantum many-body phases. In this work, we focus on a driven-dissipative Hamiltonian model based on the phononic dynamics related to a one-dimensional chain of trapped ions.

Controlling the propagation and amplification of signals provides important advantages in different applications related to quantum technologies. On one hand, robust to disorder amplification allows the read-out of weak fields with an exponential gain while attenuating the unwanted noise. On the other hand, directionality of the signal enhances the control of the output field and reduces back scattering. Combining both features achieved by topological effects, trapped ions technologies constitute a promising candidate for processing quantum information and also a key resource for quantum sensing and metrology, going from axion Dark Matter detectors [1] to very precise measurements in material science [2].

For more information, see Ref. [3, 4, 5, 6]

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Barium Fluoride Deceleration Using Temporary Ionization

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For two decades, the direct production and manipulation of cold molecules has remained a challenging task with exciting perspectives related to precision measurements and quantum chemistry. Our experimental setup at *Laboratoire Aimé Cotton* is a cold supersonic beam machine seeded by Barium Fluoride (BaF) molecules. The objective is to efficiently decelerate molecules with interest for high precision measurements such as the electron electric dipole moment [1] and the proton-to-electron mass ratio.

While a deceleration based on the dipolar force is commonly used for light molecules, it is not efficient for heavy ones like BaF because a long deceleration length would be needed for the molecules to acquire a small velocity. This is why I will present our new deceleration method using the electric force on temporary ions, which is currently being implemented in our experiment.

Two processes are being studied involving different temporary ions : the first one uses BaF^+ and the second one BaF^- [2]. Both are consisting in three main stages. For the process involving BaF^+ ions, BaF molecules inside the supersonic beam are first ionized by a pulsed OPO laser. The formed BaF^+ ions are then slowed down thanks to an uniform electric field generator placed in the path of the molecular beam. Once the ions have a small velocity, the objective is to neutralize them to get back to BaF molecules, thanks to a charge transfer between cesium atoms excited in Rydberg states and the ions. The electron in the outer shell of a Rydberg atom is weakly bound making an electron transfer possible.

On the other hand, the process involving BaF^- ions is starting with a charge transfer between cesium atoms excited in Rydberg states and neutral molecules which forms BaF^- ions. As in the first process, the ions are then slowed down thanks to an electric field. Finally, the ions neutralization can be realized by applying an electric field ramp for example. The interest of this method is that the formed ions are dipolar ions meaning that the potential, created by BaF due to its large permanent dipole moment, is deep enough to trap an electron in it [3]. The small energy needed to neutralize the ions would then not affect the internal state of the molecule.

Supersonic beams require an efficient slowing in order to increase the interaction time with the molecules and thus the measurement accuracy. This new deceleration method by temporary ionization seems suitable for heavy molecules and still has to be demonstrated experimentally. The influence of various parameters such as the densities or the initial states on the charge transfer and its efficiency also have to be investigated.

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Instabilities of superfluids in optical lattices under Floquet driving

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Ultracold atoms held in optical lattice potentials have emerged as promising candidates for quantum simulators and quantum computation. In particular, Floquet engineering, manipulating the system's properties by applying a periodic driving, plays a crucial role in generating artificial gauge fields and exotic topological phases. However, driving-induced heating and the growth of phonon modes limit its applications in interacting many-body systems. In this work we study the stability of a driven Bose-Hubbard model over a wide range of driving frequencies. At high frequencies the response of the system is chiefly governed by parametric resonances, while at low frequencies modulational instabilities, similar to those seen in static systems, become important. At intermediate driving frequencies an interesting competition between the two types of instabilities will occur. We experimentally confirm the presence of these instabilities, in both untilted [1] and tilted [2] lattices, and probe their properties. Our results allow us to predict stable and unstable parameter regions for the minimization of heating in future applications of Floquet engineering.

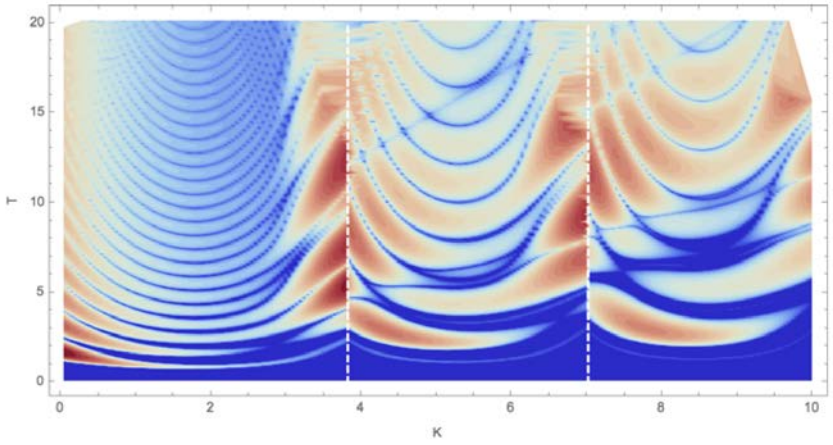

Figure 1: Stability of a tilted driven Bose-Hubbard model, as a function of the amplitude K and the period T of the driving. Blue regions are stable, while red areas are unstable.

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Molecular effects on muon transfer rate from muonic hydrogen to oxygen

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The unique characteristics of the muonic atoms offer an opportunity to accurately measure some fundamental physical quantities [1, 2] as, for instance, proton's Zemach radius [2, 3]. To that matter, the precise knowledge of the (energy-dependent) transfer rates of muons from hydrogen to the respective heavier elements is of crucial importance. Specifically, the energy dependence of the muon transfer rate from hydrogen to oxygen $\lambda_{pO}(E)$ has been determined in [4] based on FAMU collaboration's measurements [2]. Theoretically, $\lambda_{pO}(E)$ has been studied by several authors [5, 6, 7]. However, the latter calculations focus on the muon transfer rate to a single atom, whereas the real experiments involve molecular oxygen. Here we investigate the implications of oxygen molecular structure – vibrations and rotations – on the muon transfer rate. We establish that, depending on the energy distribution over the translational and internal degrees of freedom, the change in the transfer rate may vary from moderate to significant and accompanied with qualitative changes. These deepen our understanding of the transfer processes of muons to diatomic molecules such as oxygen and enable improvements of the theoretical computations. Thus, the presented results will contribute to the proper analysis of the experimental data generated by collaborations such as FAMU.

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Time-continuous measurement of position and momentum of a particle

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We present a model that focuses on the frequent measurement of a quantum particle's position and momentum, addressing the measurement problem in quantum mechanics. We propose an open system framework designed to describe a particle under interrogation by a grid of detectors uniformly distributed in phase space. We treat the particle as an open system coupled to the 'reservoir' of detectors. The evolution of the density operator ρ_S is assumed to be described by the Gorini-Kossakowski-Sudarshan-Lindbladquation:

$$\dot{\rho_S} = i[\rho_S, H_S] + \mathcal{L}_{relax}(\rho_S), \tag{1}$$

where $\mathcal{L}_{relax}$ is of the Lindblad form:

$$\mathcal{L}_{relax} = -\frac{1}{2}\sum_{\alpha}\left(C_\alpha^\dagger C_\alpha \rho_S + \rho_S C_\alpha^\dagger C_\alpha\right) + \sum_{\alpha} C_\alpha \rho_S C_\alpha^\dagger, \tag{2}$$

for which the jump operator C_α, corresponding for the measurement process, is proportional to the projector onto the coherent state $|\alpha\rangle$:

$$C_\alpha = \sqrt{\gamma}|\alpha\rangle\langle\alpha|. \tag{3}$$

Here γ is a coupling strength determining the characteristic detection frequency and α enumerates the pre-selected subset of coherent states corresponding to the positions of meters in the phase space.

This way the formalism incorporates a wavefunction collapse postulate, where after measurement, the system is assumed to be in one of the meter's states—a coherent state of a local quantum oscillator [1]. We provide trajectories of observables generated using the Wave Function Quantum Monte Carlo method as straightforward illustrative examples. Fig.1 shows a particular, single realization of the time evolution of the probability distribution of position of a free particle initially resting at $x = 0$. Discontinuities visible in figure, correspond to the moments where the meters "click" and the wavefunction is projected onto the state of the clicking detector.

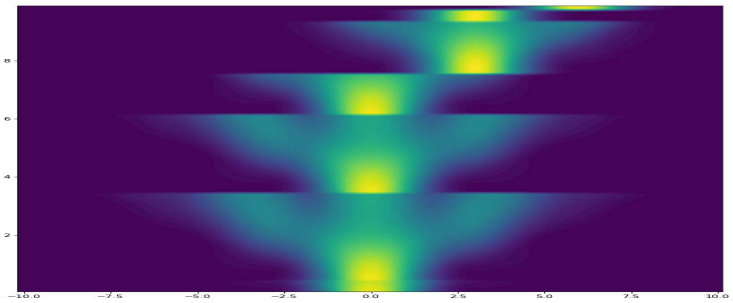

FIG. 1: Probability distribution in the position space as a function of time of a particle initially resting at $x = 0$. Jumps due to the interrogation by the meters result in discontinuities visible in figure.

The Zeno effect is predicted, particularly for a relatively sparse spatial grid of detectors. Classical trajectories emerge for densely distributed meters. The statistical characteristics of these trajectories are analogous to those obtained in the classical dynamics of a particle undergoing Brownian motion [2].

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Breaking Boundaries: Rydberg Atom Experiments in Topological Frustration

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What happens when you combine frustration and quantum effects? This question has been addressed in recent years, investigating several properties of so-called topologically frustrated systems with various types of interactions. Thanks to these studies, several unexpected properties have been revealed. Among them, we can include the destruction of the typical antiferromagnetic order [1], the increase in both entanglement [2, 3] and complexity [4], the emergence of new quantum phase transitions [5], characteristically different behaviors of the Loschmidt echo in out-of-equilibrium settings [6], etc.

While these results have been obtained through analytical and numerical approaches, it is time to test them experimentally. I will show our approach for an implementation using atomic systems based on Rydberg atoms [7]. Topologically frustrated systems being gapless, it is hard to achieve a faithful ground state preparation and to hedge against various experimental imperfections. Nonetheless, I will present various accessible quantities which, starting from a more achievable Néel state, signal the difference between a topologically frustrated system and one not. Within this framework, I will thus discuss how indeed certain geometries connected to suitably chosen boundary conditions produce robust experimentally observable differences.

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Self-organized supersolidity in ion doped Helium droplets

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It is well known that crystallized shells, of Helium atoms, a so called snowball, forms around the ion in the otherwise (super-)fluid Helium droplet [1]. Here, we show that for sufficiently large droplets a third regime appears between the snowball and the liquid one with a supersolid structure where the Helium density exhibits a periodic modulation of the particle density on a spherical shell. The periodic modulation emerges due to the inner shell snowball structure that provides a lattice substrate for the outer droplet shells yielding an accumulation of superfluid particles. To identify supersolidity in a geometrically confined scenario of a droplet we combine modified density functional theory (DFT), allowing us to describe large enough droplets, with a Gaussian Imaginary Time Dependent Hartree (G-ITDH)[2] method which traces the emergence of crystallized structures. Our approach works well as a comparison to Quantum Monte Carlo results [3] for smaller droplets reveals.

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Scale-invariant phase transition of disordered bosons in one dimension

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Bosonic particles with local interactions in one dimension (1D) are described by a universal harmonic theory, known as Luttinger liquid (LL). Diagonal disorder induces an instability in LL towards a non-superfluid Bose glass (BG) phase – a compressible insulator displaying exponential decay of off-diagonal correlations. The disorder-induced quantum phase transition between superfluid and non-superfluid states of bosonic particles in one dimension is generally expected to be of the Berezinskii-Kosterlitz-Thouless (BKT) type [1, 2]. In this work [3], we consider the disorder-induced localization transition in 1D superfluids of bosons with power-law hopping decaying with distance as $1/r^\alpha$. Here, we show that hard-core lattice bosons with integrable power-law hopping decaying with distance as $1/r^\alpha$ – corresponding in spin language to a XY model with power-law couplings – undergo a non-BKT continuous phase transition instead. We use exact quantum Monte-Carlo methods to determine the phase diagram for different values of the exponent α, focusing on the regime $\alpha > 2$. We find that the scaling of the superfluid stiffness with the system size is scale-invariant at the transition point for any $\alpha \leq 3$ – a behavior incompatible with the BKT scenario and typical of continuous phase transitions in higher dimension. By scaling analysis near the transition point, we find that our data are consistent with a correlation length exponent satisfying the Harris bound $\nu \geq 2$ and demonstrate a new universal behavior of disordered bosons in one dimension. For $\alpha > 3$ our data are consistent with a BKT scenario where the liquid is pinned by infinitesimal disorder.

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Nonequilibrium properties of the self-localized impurities in a Bose–Einstein condensate

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Solitons, and more generally nondispersive solitary waves, appear in many physical systems. The paradigmatic example is atomic Bose–Einstein condensates (BECs), well described by classical fields [1, 2]. Recently we have shown that the strongly correlated impurities immersed in a Bose–Einstein condensate (BEC) can form a bright soliton-train equidistantly arranged by Fermi wavevector as a consequence of a BEC-mediated attractive self-interaction and ordering due to the exclusion principle [3, 4]. In contrast to the dynamical instability-induced induced soliton-train [2], impurities embedded in a Bose-Einstein condensate naturally form a soliton-train as it is their ground state. It is, therefore, possible to controllably obtain stable soliton-train states without relying on unstable nonequilibrium processes. Moreover, the study of the quantum statistical nature of soliton states is usually prevented due to the inherent classical field nature of the Bose-Einstein condensate. The soliton-train states of the impurities in a condensate are strongly correlated, and considering the bosons in the TG regime or fermions, we show how this can significantly affect the properties of the solitons.

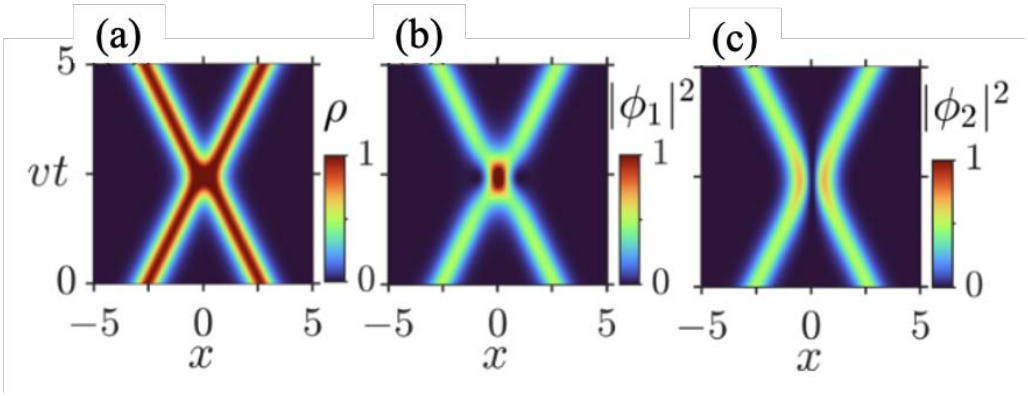

Figure 1: Dynamics of the two fermionic impurities in the BEC initially prepared at ground state for (a) total density, (b) the single particle ground state and (c) first single particle excited state.

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Toward subradiance in ordered arrays of dysprosium atoms

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Being able to trap single atoms has proven to be a useful tool for investigating quantum physics and for developing quantum technologies. The first single atom experiments were done using alkali atoms such as rubidium [1] but soon this tool was extended to alkaline earth species such as ytterbium and strontium [2][3] as well as to molecules [4]. We have generalized single atom trapping to lanthanide atoms as we report trapping and imaging of single dysprosium atoms in optical tweezers in magic conditions [5].
Using this new platform, we will study collective dissipation which is interesting for future quantum technology applications. In fact, dissipation is a limitation for current quantum simulation and computing platforms, meaning that harnessing this dissipation is an important challenge. When radiating emitters are placed at a distance of the order of λ from each other, collective effects namely subradiance and superradiance start to emerge as the dipoles can couple to one another at these distances [6]. It is however important that the atoms be spatially well confined which is not possible using only tweezer arrays. We therefore added an optical lattice to our setup for axial confinement allowing us to work with atoms in isotropic traps.
Furthermore we make use of the many transitions of dysprosium and their different linewidths to image site resolved excitations therefore making it possible for us in the future to extract the dynamics of the collective effect.

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Statistics of light emitted from interacting quantum emitters: photons emitted in the Zero-Phonon Line and Stokes-shifted photons

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Quantum emitters such as fluorescent organic molecules and quantum dots can exhibit an extremely narrow emission line at cryogenic temperatures. These emitters behave as efficient single-photon sources when isolated, and thus they are promising candidates for quantum information and quantum optics applications [1]. Additionally, superradiant and subradiant states emerge when various emitters interact. To identify potential applications of these systems, we investigate the statistics of light emitted from two interacting emitters under different illumination and detection schemes. In particular, we analyze the intensity correlation $g^{(2)}(\tau)$ that can be measured with the Hanbury-Brown Twiss (HBT) coincidence setup (see Fig. 1a).

We first study the correlation of photons emitted in the Zero-Phonon Line (ZPL), corresponding to the purely electronic transition. We find that the intensity correlation can be tailored from strong antibunching to strong bunching by tuning the laser frequency and/or intensity (see Fig. 1b). Thus, this system constitutes a versatile source of light that could find use in the engineering of photon sources. Additionally, we show that $g^{(2)}(0)$ measurements can be exploited to access experimental information about the emitters and their coupling.

On the other hand, low-temperature single molecule fluorescence experiments are based on the resonant excitation of the ZPLs and the detection of the Stokes-shifted fluorescence filtered from laser photons [2]. To address this issue, we propose a model which goes beyond the usual description of the emitters as two-level systems and takes into account the vibrationnal levels of the molecular ground electronic state. Considering again the case of two interacting emitters, we compare the light statistics of Stokes-shifted photons and the statistics of photons emitted in the ZPL, and show that they can be drastically different (see Fig. 1c). Additionally, we show that the recent experimental results in Ref. [2] can be accurately described only when analyzing the Stokes-shifted photons. These results stress the importance of including the proper photon filtering in the theoretical description of each experimental configuration.

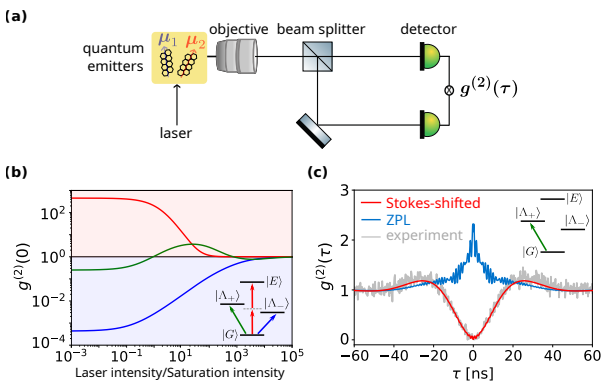

Figure 1: (a) Sketch of the HBT setup. (b) Intensity correlation $g^{(2)}(0)$ of photons emitted in the ZPL when the laser is tuned to (red) the two-photon resonance, (blue) the superradiant state and (green) the subradiant state. (c) Intensity correlation $g^{(2)}(\tau)$ of (red) Stokes-shifted photons and (blue) photons emitted in the ZPL when the laser is tuned to the transition frequency of the subradiant state. The gray line corresponds to the experimental data reported in Ref. [2].

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Overtone spectroscopy of HCO^+ and HOC^+ ions

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The HCO^+ ion ranks among the prevalent cations in the interstellar medium [1], following closely behind H_3^+ ions. Its presence has been observed across a diverse array of celestial objects, including giant molecular clouds like Orion, regions of intense star formation, dense areas within the diffuse cloud surrounding Cygnus OB2, comets, and the expansive expanse of the interstellar medium [2].

The first overtone transitions ($20^00 \leftarrow 00^00$) of HCO^+ and HOC^+ were measured with 22 pole ion trap using a laser induced reaction and in separate stationary afterglow with Cavity Ring-Down Spectroscopy experiment. These experimental setups led to the determination of spectroscopic constants of the upper $2v_1$ state for both HCO^+ and HOC^+. At the same time, the corresponding radiative lifetimes of $2v_1$ were obtained. The quenching reaction rate coefficients for collisions of HCO^+ in $2v_1$ vibrational state with He, H_2 and N_2 were also measured.

Acknowledgment

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Electromagnetic Dipoles for Simulation of Complex Models on Quantum Magnetism

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We will describe current progress with our apparatus of ultra-cold dysprosium (Dy) atoms. The main scientific tool of the apparatus is a high-resolution microscope (1). Specifically, we have undertaken steps in positioning the atoms, into the focal plane of the microscope and engineering a single 2D atomic plane commensurate with the last. The idea is based on the properties of a beat-note lattice (BNL) composed of two colors (2) in the deep lattice regime. Supplemented with precise parametric heating and the positional dependence of the band gap of the BNL we aim to select precisely a single atomic plane. Furthermore, our current effort to engineer a 2D matter wave magnification (3) in an incoherent optical trap will be outlined.

The main ingredient in our proposal for initiating an electric dipole-dipole interaction (DDI) in Dy is a pseudospin selected by microwave dressing of a unique nearby-spaced opposite parity doublet (OPD). First spectroscopy based on Electromagnetically induced transparency of this OPD will presented. Further plans of utilizing Stimulated Raman Adiabatic Passage supplemented by a microwave for the efficient population of the OPD will be outlined.

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Rydberg-Rydberg Interaction Strengths and Dipole Blockade Radii in the Presence of Förster Resonances

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Achieving a substantial blockade radius [1] is crucial for developing scalable and efficient quantum communication and computation [2].

In this theoretical study [3], we present the enhancement of the Rydberg blockade radius by utilizing Förster resonance [4]. This phenomenon occurs when the energy difference between two initial Rydberg states closely matches that between the corresponding final Rydberg states, giving rise to a resonant energy transfer process. We employ quantum defect theory to numerically calculate the ^{87}Rb–^{87}Rb Rydberg atomic pair, enabling us to accurately estimate the van der Waals interaction. By conducting an in-depth investigation into various Förster resonance transitions within the p and d manifolds of a ^{87}Rb atom pair, we have achieved a profound understanding of the dipole-dipole interaction strength and the corresponding dipole blockade radius for each transition.
Our analysis of the dependence of the Förster defect when the initial principle quantum numbers of two Rydberg atoms are not significantly different revealed that the Förster transitions are unsuitable for achieving dipole blockade.
However, a remarkable breakthrough emerged when the initial principle quantum numbers of two Rydberg atoms differ by a value greater than 10. We observed that the Förster defect approaches zero in numerous cases, resulting in a singularity of the C_6 coefficient. In some transition channels, we found that a giant blockade radius exceeding 23 μm (the current largest measured blockade radius in experiments) can be achieved, with the most extensive blockade radius above 50 μm present.

The significance of our work lies in the substantial enhancement of the dipole blockade effect in terms of both interaction strength and distance. These outcomes will ignite interest in exploiting strong interactions in atom pairs to establish long-range coupling, and enable larger-scale quantum operations and advances quantum technologies, with broad implications for achieving long-range quantum entanglement and robust quantum processes.

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Semi-empirical predictions of energy levels, Landé g_J factors and hyperfine structure for the odd–parity configuration system of Co I

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Atomic cobalt has gained significant attention in various astrophysical studies (stellar atmosphere models, galactic evolution hypotheses), but it also shows promising properties for quantum engineering, as a candidate for Bose-Einstein condensation. Achieving the ultra–cold temperatures necessary for condensing atoms requires specialized laser cooling systems tailored to the specific element, which, to our knowledge has never been investigated before. The initial step toward creating a BEC on cobalt cloud requires a systematic and detailed analysis of the energy structure and radiative transition parameters within Co I. We present the preliminary results of multiconfiguration semi–empirical calculations of the fine structure (*fs*) and the hyperfine structure (*hfs*) for the odd-parity level system of atomic cobalt (Co I), using all available experimental data. This new data was obtained using our proprietary software package designed to analyze complex atom structure. The method of parameterization of the atomic structure and the appropriate program package have been developed for many years by Dembczyński, Elantkowska and Ruczkowski [1].

The considered configuration system consisted of 22 odd configurations: $3d^8n'p$ (n′=4–9), $3d^8n'f$ (n′=4–6), $3d^74sn'p$ (n′=4–9), $3d^74sn'f$ (n′=4–6), $3d^74s^2n'p$ (n′=4–5), and $3d^74s^2n'f$ (n′=4–5). Using the iterative fine-structure calculation procedure, predictions of energy levels along with their Landé g_J factors and wave functions were obtained for each electronic state. The obtained eigenvectors were used next in the process of *hfs* evaluation.

The attained wave function, along with the previously evaluated eigenvectors of the even–parity level system [3], will be utilized next for the parametrization of the radiative parameters and lifetimes for Co I in future studies. All these stages will be crucial for future analysis of cobalt utilization in quantum engineering. We hope to achieve a good agreement between the theoretical hyperfine structures and the experimental constants, which will confirm the validity of the obtained eigenvectors. Additionally, for levels without known experimental *hfs* constants, the values will be predicted. We will also provide a preliminary reassessment of Pickering's propositions [2] in spectroscopic descriptions of the observed Co levels.

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The double minimum $E^1\Sigma_u^+$ state in Cs_2

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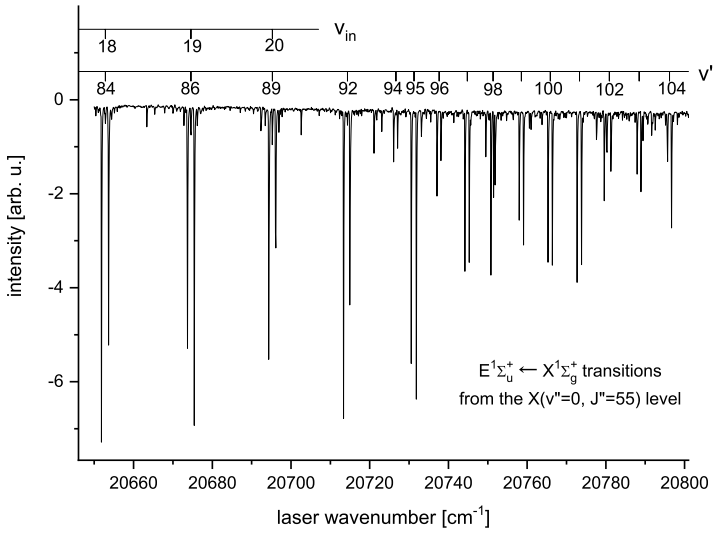
We present experimental study of the double minimum E(3)$^1\Sigma_u^+$ state in Cs_2 for which only fragmentary data related to the inner potential well had been available [1]. This state was suggested for photoassociation experiments in ultracold environment by Pichler *et al.* already 20 years ago [2] but surprisingly has eluded further spectroscopic investigation and the proposal by Pichler *et al.* has never been realised. In the present experiment, using the polarisation labelling laser spectroscopy technique (PLS), we observed more than 8000 spectral lines corresponding to transitions from the ground electronic state $X^1\Sigma_g^+$ of caesium dimer to the investigated excited state, most of them terminating on levels lying above the inner potential barrier. Part of the typical polarisation spectrum of the E $\leftarrow$ X system is shown below. Transitions to the regions below and above the internal potential barrier can be easily distinguished by a distance of consecutive PR doublets. Quantum numbers v' denote absolute numbering of the vibrational levels, whereas labels v_{in} correspond to independent numbering only of the levels supported by the inner well.



Aided by theoretical calculations by Spies [3] we constructed a potential energy curve of the $E^1\Sigma_u^+$ state. We applied the single channel version of the Fourier Grid Hamiltonian (FGH) code from Ref. [4] combined with the nearest-energy strategy for assigning molecular levels. The resulting potential allows to reproduce energies of the rovibrational levels involved in the observed transitions with 0.05 cm^{-1} accuracy. The position and height of the barrier on the potential curve was determined.

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Towards the development of electron-ion trapping system for microwave sensing at room temperature

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Trapped electrons are anticipated to play a vital role in various quantum technologies due to their higher secular frequency compared to ions. Given the inherent spin states without additional internal states, a qubit realization is one of the applications [1], single microwave photon detection with a trapped electron [2], quantum metrology protocols [3], etc are several others. In this contribution, we present the concept of a levitating electron coupled with a laser-cooled ion system that will serve as a means of detecting weak microwave signals without using dilution refrigerators for the preparation of electrons in the ground state.

Unlike notable experiments with electrons in Penning traps [4] or solid state detectors [5, 6, 7], ours are designed to utilize the electron-ion coupled system trapped in a dual-frequency Paul trap at room temperature as the detection medium. The high-frequency signal (GHz), amplified by a $\lambda/2$ resonator for electron trapping, and the low-frequency signal (MHz) applied to end caps for ions are manageable by our homemade 3D-printed coaxial trap with a high quality factor of more than 1000 in GHz regime. We devised a 3D-printed atomic source for the controlled production of ions and cold electrons from atomic beam while maintaining room temperature inside a vacuum chamber. We adopted a wavelength-tunable laser in assistance with LED for the photoionization of $^{40}\mathrm{Ca}$ atoms to produce ions and cold electrons. Trapped ions together with cold electrons in our deep potential depth of up to 4000 K (as per COMSOL computations) for GHz will serve the purpose of sympathetic cooling of trapped electrons.

Currently, we are testing loading of the electron-ion two particle system into the trap. In this update, we will share our most recent experimental findings pertaining to the trapping of electron-ion pairs. On the theoretical front, we are investigating the interactions of the cold electron-ion pair in the environment of the trap. Particularly, we are dealing with classical and quantum mechanical models to enlighten the exchange of energy between the electron and the ion mediated by the trap.

ACKNOWLEDGMENTS. This work is supported by the Czech Science Foundation (GAČR: GA24-10992S), by the Primus Research Programme (PRIMUS/21/SCI/005), and by the Charles University Grant Agency (GAUK 295023). We also acknowledge the support from the Czech Ministry of Education, Youth and Sports (project QM4ST, reg. no. CZ.02.01.01/00/22_008/0004572).

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Subwavelength potentials for ultracold atoms using dark states

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This presentation reports on possible manipulation of cold atoms using optical potentials and quasi-random fields.

Building upon recent developments in three-level Λ configuration schemes (see [3]), we extend the approach to a four-level tripod configuration, creating a spin 1/2-like two-dimensional dark space with 1D motion and external gauge fields. The resulting dark subspace motion exhibits a significantly increased lifetime compared to similar Λ systems, opening up possibilities for studying frustrated systems with various hopping amplitudes in the lattice. For more information, see Ref.[1]

Furthermore, a quasi-random potential for cold atoms is constructed using dark states emerging in Λ level configuration, employing speckle laser fields to introduce randomness. The study of Anderson localization in these potentials reveals a decreased localization length due to the non-linear fashion of obtaining dark-state potential, resembling features found in random Kronig-Penney-type Hamiltonians. . For more information, see Ref.[2].

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Thermal melting of a vortex lattice in a quasi two-dimensional Bose gas

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In the context of quantum simulation, there is a profound analogy between a two-dimensional system of neutral atoms in fast rotation and the problem of 2D electrons in a magnetic field, providing a mapping with the quantum Hall effect [1]. Here we present the first observation of the thermal melting of the vortex lattice present in a rotating quasi two-dimensional (2D) superfluid Bose gas. A superfluid Bose-Einstein condensate is prepared in an oblate trap generated by dressing atoms placed in a quadrupole magnetic field with a radio-frequency field [2]. The atomic cloud is set in rotation by rotating a deformation of the trap [3]. The superfluid then hosts a triangular lattice of quantized vortices in a quasi-2D regime. The order of the lattice is progressively destroyed as the superfluid effective rotation rate increases. This situation enables to test if the scenario for the thermal melting of a 2D crystal proposed by Kosterlitz, Thouless, Halperin, Nelson and Young (KTHNY) is relevant for a vortex crystal in a quantum gas. The vortex lattice's translational and orientational order are characterized respectively by the pair correlation function and the angular correlation function, and we show that the evolution of these order functions with an effective temperature evidences a transition to a liquid state and is consistent with the KTHNY scenario involving the unbinding of 5-fold and 7-fold defects of the lattice. This result paves the way to the understanding of the influence of temperature as a 2D quantum system reaches the Lowest Landau Level regime, which corresponds in our case to the situation when the effective rotation rate of the superfluid approaches the radial trapping frequency.

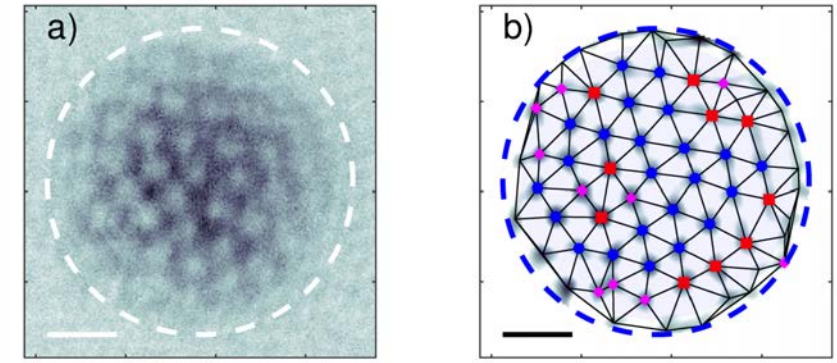

Figure 1: a) Vortex lattice after time-of-flight. b) Delaunay triangulation indicating lattice sites with 6 (blue dots), 5 (magenta diamonds) and 7 (red squares) neighbors.

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Similarity of quantum-mechanical states: Analytical and numerical studies for central potentials

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Quantum similarity functionals were introduced for the purpose of quantifying the greater or lesser similarity among charge distributions of molecular systems [1] later applied in a diversity of physical contexts [2, 3]. In this work we focus on applications of the Quantum Similarity Measure (QSM) and the Quantum Similarity Index (QSI) for comparing the electron densities associated to different states of physical systems governed by central potentials. A numerical and analytical study of these comparative functionals has been carried out, specifically for the D-dimensional hydrogen atom [4] and the D-dimensional harmonic oscillator [5]. In both cases the analysis of these functionals is grounded on the quantum numbers of the states involved, and the dimension of the system as well. Parallel studies in position and momentum spaces provide us with information on the similarity of states in the respective conjugate spaces. In addition, a detailed analysis has been performed in both systems, by considering the separate contributions of the radial and angular parts to the whole similarity.

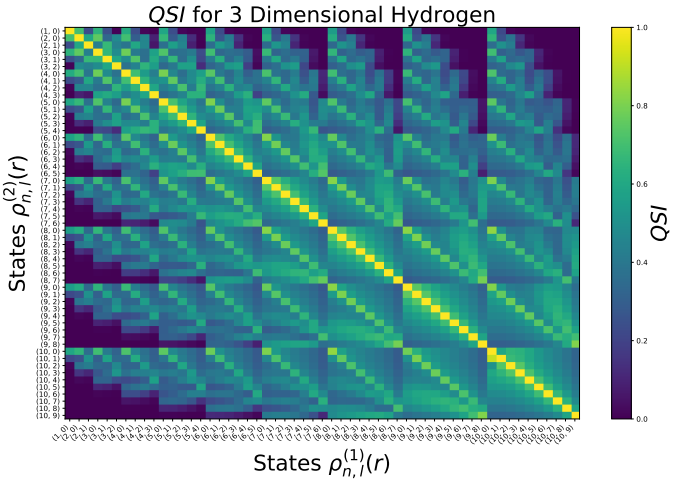

Figure 1: QSI for different pairs of states (n, l) of the radial part of the 3-dimensional hydrogen atom.

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Dynamics of Rydberg state population of slow highly charged ions in the nanostructure creation process: Theoretical model

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We propose a theoretical model to investigate nanofeatures creation on the metal surface by an impact of slow Rydberg ions. The model comprises the quantum two-state vector model (TVM) [1] and micro staircase model for studying the neutralization process above the surface [1] and the ion-atom interaction potential model for studying the kinetic energy loss below the surface [2]. The characteristics of the TVM is the active electron state is described by two wave functions $\Psi_1(\vec{r},t)$ and $\Psi_2(\vec{r},t)$ evolving in opposite directions in time. In that way, initial (electron is mainly localized in the metal) and final (electron is bound to the ion in Rydberg state) conditions influence the intermediate surface modification stages. Once neutralization finishes in front of the solid, the ion at the final charge state penetrates the solid and elastically and inelastically collides with target atoms, losing its kinetic energy. The total energy, comprising the neutralization and the deposited kinetic energy, deposits into the solid, inducing the surface modification and nanostructure creation as a hillock or a crater (ring), which depends on the ionic velocity [2, 3].

The process of surface nanostructure creation by an impact of slow Rydberg ion can be described as follows. Above the surface, the slow highly charged ion (HCI), approaching a target, captures electrons in the highly excited (Rydberg) states. The process is described by the intermediate neutralization probability $P_{\nu_A}(t)$ calculated via the mixed flux $I_{\mu_M,\nu_A}(t)$ [1, 2]. The quantity $I_{\mu_M,\nu_A}(t)$ is determined by the two amplitude $\rho_{12}(\vec{r},t) = \Psi_1(\vec{r},t)\Psi_2^*(\vec{r},t)$ and the two current density $\vec{j}_{12}(\vec{r},t) = (\Psi_2^*\vec{\nabla}\Psi_1 - \Psi_1\vec{\nabla}\Psi_2^*)/(2i)$, which points out the effect of the initial and final conditions on the surface modification. Simultaneously with the Rydberg state population of HCI, the neutralization energy deposits into the solid, leading to the first surface destabilization and rearrangement of target atoms. Below the surface, due to kinetic energy loss, additional energy is deposited into the solid, causing further modification. The nuclear stopping power and the deposited kinetic energy are determined via the nuclear stopping cross section calculated by using the classical scattering theory [2].

The theoretical prediction that a specific nanostructure is formed as a function of ionic charge and velocity is supported by recent experimental data [3] considering the impact of slow highly Xe^{q+} ions on gold and titanium targets [3]. In addition, the nanofeatures sizes (diameters) derived within the model, are also consistent with the experimental data [3, 4].

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Zeeman-Sisyphus Deceleration of CaF Molecules

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Building on the established work with ultracold atoms, cold molecules offer exciting possibilities for quantum simulation and tests of fundamental physics due to their more complicated internal energy structure and longer-range dipole interactions. Laser cooled molecules, compared to those associated from atoms, benefit from efficient imaging techniques as well as offering broader range of molecular species. However the direct cooling of molecules also presents new experimental challenges. For instance, the capture velocity of molecular magneto-optical traps (MOTs) is only around 20 m/s which places great importance on the use of efficient slowing techniques for effective MOT loading.

Direct laser slowing can be applied to a limited subset of molecules. This technique is impractical for other molecular species due to the around 10^4 photons required to bring the molecular beam to rest. These species include those with unfavourable branching ratios, which will be quickly lost from the slowing cycle without several repumps, and heavier polyatomic species which require an even greater number of scattered photons. Additionally the transverse divergence of molecular beams leaving a source limits the number which can be loaded into a MOT.

Zeeman-Sisyphus deceleration presents a novel way to address both of these concerns. Molecules travel through a spatially varying magnetic field and are optically pumped between high and low field seeking states, meaning they continually climb a potential hill. The optical pumping requires at least two orders of magnitude fewer photons to be scattered compared to direct laser slowing, while the magnetic field can be engineered to also provide transverse guiding. Zeeman-Sisyphus deceleration is additionally a time-independent technique which allows long molecular pulses or continuous beams to be efficiently slowed.

Zeeman-Sisyphus deceleration has previously been demonstrated for CaOH [1] and YbOH [2], in a two stage decelerator made up of cryogenically cooled superconducting solenoids. Here, we present our progress in building upon this work to experimentally realise a Zeeman-Sisyphus decelerator for calcium monofluoride (CaF). Our implementation follows [3], using 80 stages of permanent magnets at ambient temperatures.

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Understanding collisions of a free atom with a trapped ion

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We have developed a theoretical model to describe the collision of a free atom with a trapped ion at ultracold temperatures that treats the system as an effective three-body problem in which the trap center acts as a third particle. The pairwise atom-ion interaction includes the long-range polarization potential and an energy-independent quantum defect that accounts for the short-ranged phase of the two-body wavefunction at zero energy. We begin with a simplified model in one spatial dimension. A hyperspherical treatment reveals the presence of collisional resonances arising from the confinement of the ion. A preliminary calculation of the hyperradial potential curves in three spatial dimensions sets the stage for understanding such resonances in realistic systems.

Linear polar molecule in a rotating electric field: exploring the adiabatic limit

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Different configurations of electromagnetic fields are used to guide and deflect [1, 2, 3] ultracold molecules. In these experiments, not only their translational degree of freedom is controlled and manipulated, but also their internal degrees of freedom (electronic, vibrational and rotational) are significantly affected. The field-control of their rotational dynamics gives rise to two main phenomena: their alignment [4], which implies that the molecular fixed axes are confined along the laboratory fixed frame; and the orientation [5], which adds a well defined direction of the electric dipole moments.

In this work, the static in-homogeneous electric field used experimentally to guide and deflect polar molecules is described by assuming a fixed spatial position of the molecule and a rotating time-dependency of the electric field. By considering the molecule in a fixed electronic and vibrational state, and within the Born-Oppenheimer and rigid rotor approximations, we investigate the impact of this field in the rotational dynamics. By using the rotational period as a characteristic time, the adiabatic limit is explored for slower and faster rotation times. We encounter an adiabatic dynamics, even for thermal samples of molecules, for which the electric dipole moment follows the field direction, being the molecules oriented along this instantaneous axis.

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Characterization of hybrid rf-dc optically-pumped magnetometer at Earth's magnetic field

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In this work we demonstrate hybrid *optically pumped magnetometer* (hOPM) able to measure simultaneously one dc field component and one rf field component quadrature with a single atomic spin ensemble [1], operating at Earth's magnetic field (see Fig.1). We describe optical pumping frequency and amplitude modulation schemes to achieve quantum noise limited performance, crucial for achieving maximum sensitivity. We find that the hOPM achieves sub-pT$/\sqrt{\text{Hz}}$ sensitivity for both dc and rf fields. A high sensitivity hOPM at Earth field could be used in outside-the-lab applications, including underwater magnetic communication [2], underground [3], and in planetary exploration. Quantum noise limited performance in this instrument could be improved by including squeezed states of light [4].

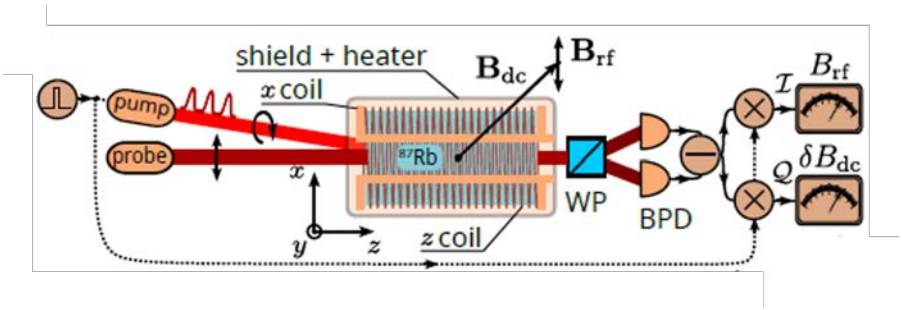

Figure 1: Experimental setup of a Bell-Bloom optically pumped rf-dc magnetometer. The setup consists of a shielded ^{87}Rb cell through which pass the probe and the pump beams. The polarization rotation of the probe is captured via a Wollaston prism (WP) and a balanced photodetector (BPD). Polarimeter signal is demodulated with respect to the optical pumping modulation.

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Search for possible laser cooling schemes in terbium atom

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The terbium atom can possibly be considered for quantum technology applications, such as electromagnetically induced transparency (EIT). Since the only stable terbium isotope is bosonic, its possible potential for the creation of Bose-Einstein condensate may also be analysed. However, for such applications, the atoms need to be cooled, in the case of BEC even to temperatures of the order of nanokelvins. For rare-earth elements a specific laser cooling method was developed, described in [1]. That paper presents a cooling scheme for erbium atoms in a magneto-optical trap (MOT), using an optical $J \rightarrow J+1$ transition from the ground state, without the need for a repumping laser. This method relies on repeated excitation of the selected optical transition without any significant loss to energy levels other than the lower level of the cooling transition. If leaks are negligible (intensity at least 10^5 times smaller than that of the cooling transition [2]), there is no need for any auxiliary excitation. There is, however, an additional requirement for a high magnetic moment (for erbium - $7\mu_B$ in the ground state), which prevents atoms at the metastable energy levels terminating the leaking transitions from escaping from the MOT by trapping them in a nonuniform magnetic field. For now, there are a few elements successfully cooled with this technique: erbium [1], holmium [2], thulium [3] and dysprosium [4]. Among, these, in Er, Dy and Ho transitions $6f^n6s^2 \rightarrow 4f^n6s6p$ $J \rightarrow J+1$ were used for cooling since they are the strongest lines in their spectra.

Atomic terbium also possesses a high magnetic moment of $10\mu_B$; there were also successful attempts of its trapping in a magnetic trap and it was precooled to the millikelvin regime [5]. It also has a transition analogous to those used for laser cooling of Er, Dy and Ho [6], which should be analysed for its possible use in cooling for this element. However, there is one important difference - in terbium there are more leaking transitions [6] than in other discussed elements. The planned semi-empirical calculations of transition probabilities should allow estimation of the relevant branching ratios. Also, some alternative transitions are considered, which can be experimentally investigated in a hollow cathode discharge lamp in order to determine the details of the hyperfine structure patterns, important for possible application of the selected *hfs* components for cooling.

The presented work has been financed by the Ministry of Science and Higher Education in Poland under Projects 0511/SBAD/00/23, 0511/SBAD/2451 at the Faculty of Materials Engineering and Technical Physics PUT and No 0711/SBAD/4662 at Faculty of Control, Robotics & Electrical Engineering PUT.

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Full control of non-symmetric molecules orientation

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Precise control over chemical reactions has long been a fundamental goal in quantum chemistry [1]. The enhancement of the reactivity relies on the probability of head-to-tail reactions of the atoms of interest within the molecule. The accurate control of the molecular orientation is essential to achieve this goal, as well as to obtain precise measurements within the molecular frame, diminishing the distortions caused by the rotational dynamics [2].

Current methods, including impulsive and adiabatic alignment by means of non-resonant laser fields [3] or brute force orientation of the permanent dipole moment using electric fields allow to control the position of the molecule in space, although restricted to specific molecular axes [4].

To bypass this constraint, we apply quantum optimal control techniques to design electric fields to orient any molecular axis along a given direction [5]. We demonstrate for non-symmetric planar molecules, taking the 6-chloropyridazine-3-carbonitrile (CPC) molecule as example, that it is possible to maximize the orientation cosine of any molecular axis along a given direction, independently of the dipole moment direction. Furthermore, we also explore the accurate control of the orientation of highly rotating molecular states, i.e., superrotors. Finally, we discuss potential applications, including the separation and selection of chiral molecules.

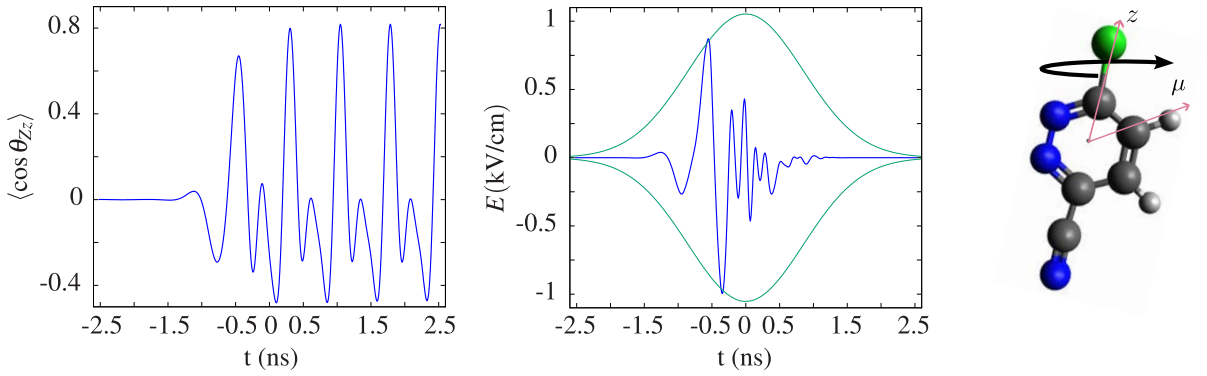

Figure 1: Orientation of the z molecular axis of the CPC molecule along the Z laboratory axis (left) during the interaction by the optimal designed driving electric field (center). A sketch of the CPC molecule is also shown (right).

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Collective driven-dissipative phenomena in dense atomic clouds

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Our research focuses on the study of the interaction between light and a dense atomic medium, which in our case is a cloud of laser-cooled Rb 87 atoms, confined by a tight optical dipole trap. The cloud is cigar-shaped, with an axial extension of tens of λ (here λ is the the transition wavelength, 780 nm, of the D_2 line of Rb 87), but a radial one of $\sim 0.5\ \lambda$.
We have recently explored how the collective coupling of the atomic cloud to the electromagnetic field modifies its response to excitation by light. In particular, we have observed Dicke [1] superradiance, subradiance [2], and witnessed atomic correlations in the medium resulting from collective driven-dissipative dynamics. Understanding these phenomena poses a challenge to many-body theories, superradiance and subradiance can have important applications in quantum technologies, such as storing the light in the atomic medium [3] and superradiant lasing [4].
On the experimental side, we're currently upgrading our set-up: we opted for a more compact configuration comprising a glass cell, in the spirit of pushing the maximum number of trapped atoms that we could previously reach and explore denser regimes. Additionally this new configuration will allow us to have more flexibility on the geometry of the optical paths for detection, excitation and trapping.

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No polaron-molecule transition in a two-dimensional Fermi Hubbard model

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A $2D$ Fermi gas interacting attractively with an impurity of different spin in the continuum undergoes, at zero temperature, a phase transition from a polaron to a molecule state. Here we study the same system but in a square lattice and, in particular, we compute the energy of the polaron and the molecule ansatzes in a $2D$ Fermi-Hubbard Hamiltonian. The polaron always remains the ground state and, hence, we do not observe a phase transition between both ansatzes even at different filling numbers. We confirm these results by solving the system using the determinant diagrammatic Monte Carlo technique with a new approach where no normalization is needed. Surprisingly, no sign problem appears in the simulation and, therefore, we can sample high-order Feynman diagrams which enables us to obtain the energy at large attractions. While the molecule ansatz at zero momentum is never the ground state, we note that the polaron picture fades as the interaction strength increases since the residue decays to zero. This study arises the question of how does this system look in the high-attraction regime.

Interaction effects on the itinerant ferromagnetism phase transition

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Itinerant ferromagnetism is one of the most studied quantum phase transitions, the transition point and the nature of this phase transition being widely discussed. In dilute Fermi liquids, this analysis has been carried out up to second-order in the gas parameter, where the results for any spin degeneracy are universal in terms of only the s-wave scattering length a_0. We extend this analysis to third-order where energies depend, not only on a_0, but also on the s-wave effective range r_0 and the p-wave scattering length a_1. The introduction in the theory of these new parameters changes the transition point, with respect to the second-order estimation, and also can modify the nature of the phase transition itself. We analyze these interaction effects on the phase transition for different spin values. The emerging phase diagram shows that the type of ferromagnetic transition changes dramatically as a function of r_0 and a_1 and, importantly, that this classification is not only a function of the spin value, as happens at second order.

Calculation of electron scattering lengths on Ar, Kr, Xe, Rn and Og atoms

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Scattering length is one of the most useful parameters for describing low-energy electron-atom collisions. It is defined as a radius of a hard sphere in the zero-energy total cross section, where the sign represents the type of interaction: it is positive for repulsion and negative for attraction. This parameter is used in a variety of calculations of different processes, for instance photoassociation of two atoms.
Focusing on the noble gases, we calculate the scattering potential using the Dirac-Coulomb Hamiltonian supplemented with a model polarization potential. We determine the scattering lengths using two methods, namely phase shifts for very small scattering energies and the shape of the wave function for zero scattering energy. We compare our theoretical electron scattering length results on Ar, Kr and Xe atoms with existing experimental and theoretical data [1]. In turn, the results obtained for the first time for Rn and Og atoms require independent confirmation. From our calculations, the scattering length of radon is $a_{Rn} = -13.2 \pm 2.1$ a.u. and of oganesson is $a_{Og} = 15.1 \pm 2.3$ a.u.. The analysis conducted indicates that the source of the greatest uncertainty in the obtained results is the literature values of dipole polarizability [2]. The study used the GRASP2018 computational package for bound states and the modified COWF code for continuum states [3].

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Negative ion production for experiments with antiprotonic atoms

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Antiprotonic atoms are exotic systems where one of the electrons is replaced by an antiproton. Such objects are unique targets for studying matter and antimatter interactions, which is the goal of AEgIS experiment in CERN [1]. Antiprotonic atoms can be created by interacting anions with antiprotons in a Penning trap. AEgIS experiment located in the Antimater Factory in CERN has direct access to the low-energy antiproton beam delivered from the Extra Low Energy Antiproton ring (ELENA). Thus, an efficient negative ion source is needed to produce antiprotonic atoms. For experimental reasons, such anions must be created in a separate apparatus, trapped in a quadrupole Paul trap, and delivered in a single pulse to the main Penning trap.

We present an anion source, which uses an electron-molecule dissociative attachment process. In the vacuum chamber (10^{-9} mbar), the iodine molecules are bombarded with monochromatic electrons. Produced negative ions are trapped in a linear Paul trap and, on demand, sent as a pulse to the main experimental chamber. The source construction and operation details will be discussed, as well as the electron dissociative attachment phenomenon.

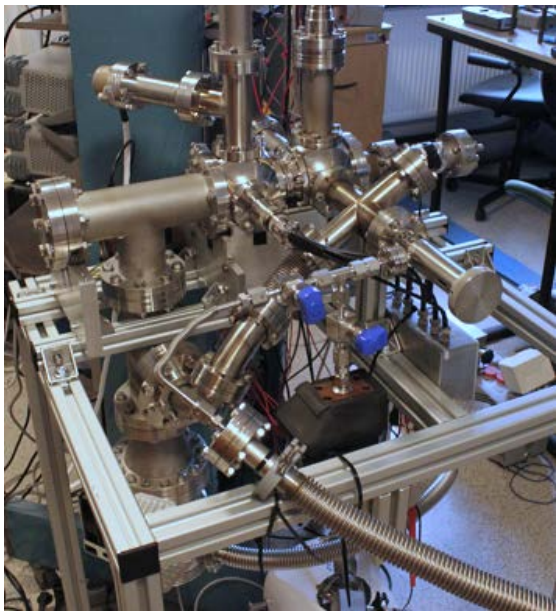

Figure 1: The negative ion source using a multi-centre quadrupole ion trap.

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Mutual neutralization with manipulated initial quantum level distributions

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Mutual neutralization (MN) is a fundamental process wherein oppositely charged ions interact, yielding two neutral products via electron exchange. The Double ElectroStatic Ion Ring Experiment (DESIREE) at Stockholm University leads research in MN experiments. It integrates long-term ion storage and manipulation capabilities with a merged-beams setup, enabling comprehensive investigations into low-energy MN studies [1]. In this work, we highlight the remarkable versatility of DESIREE in exploring MN with ions in precise excited states. Utilizing these integrated capabilities, we conducted MN experiments using Na^+ and Si^- beams, allowing us to separate contributions from the ground and excited metastable states of Si^-. Employing a continuous wave (CW) laser at 900 nm, targeted photodetachment was employed to selectively remove excited Si^- ions while leaving ground state ions unaffected, a method similar to that used in oxygen electron affinity measurements [2]. By analyzing MN measurements with and without metastable ions, we can extract the distinct contributions from each state, enabling rigorous testing of theoretical predictions and facilitating a comprehensive understanding of the MN process.

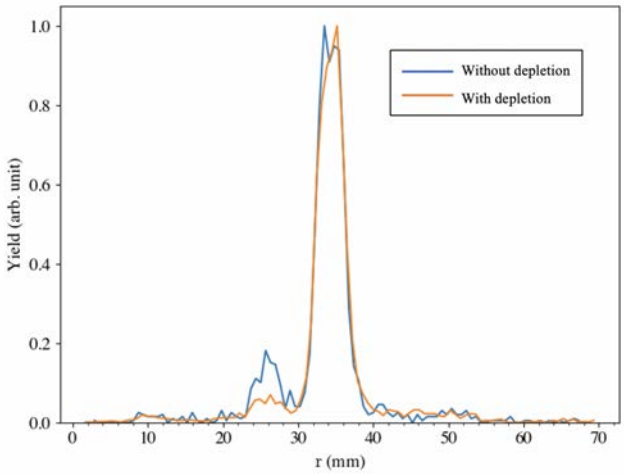

Figure 1: Yield of neutral pairs as a function of the separation r between the atomic products when their centre-of-mass reaches the detector plane.

Acknowledgments: This work was performed at the Swedish National Infrastructure, DESIREE (Swedish Research Council Contracts No. 2017-00621 and No. 2021-00155).

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The orbital angular momentum of the photon and quantum interplay with atoms

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The photon possesses many quantum variables. One of them is the orbital angular momentum (OAM) [1]. Like the polarization the OAM allows entanglement [2] and, in principle, because it ranges a large space (signed integer one) it offers the possibility for multiple entanglement which is of interest for quantum technologies .

The OAM results of the helical shape of the wavefront of the wave, currently called optical vortex beam. A crude image of the vortex beam is the endless screw for an OAM equal to one, or a fusilli pasta for an OAM equal to 2. The topological point located at the centre of the vortex beam is crucial and the key-question is to understand its role in the interaction with matter and how one can create OAM entanglement. Our purpose is to present some examples dealing with quantum interaction of vortex beams with atoms.

One example is the two-photon transition realized with vortex beams (see the figure). In rubidium, it brings the atom from the fundamental level to the 5D level. Then, the atom decays to its ground state emitting two photons, whose colours depend on the considered possible 4-level scheme. The figure shows the scheme which produces an infrared photon and and a blue one. In this phase-sensitive four-wave mixing process, the emitted photons are correlated not only by colour (energy conservation) but also by OAM if the excitation has been done using vortex beams [3]. Our works examines the possible OAM entanglement, according the handedness of the input vortex beans, according the number of OAM they contain and shows that multiple entanglement can appear depending of the used 4-levels scheme [4].

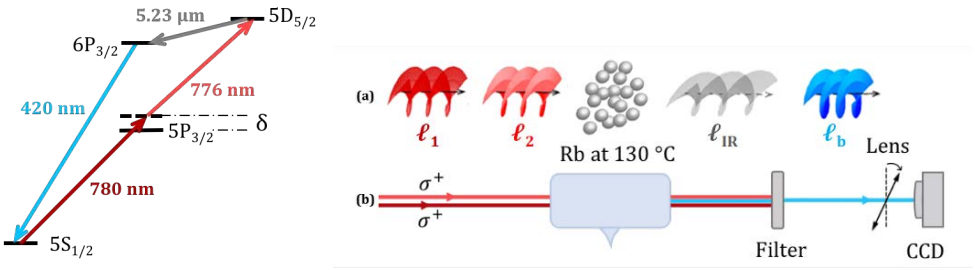

Figure 1: Four-level scheme for two-photon trnasition followed by a pair emission; experimental scheme where atoms of a cell are excited, emitted blue light analysed by the tilted lens method.

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Quantum-state engineering with magneto-optically detected nuclear magnetic resonance at ultralow magnetic fields

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Quantum-state reconstruction is a key element of many quantum-information applications, ranging from quantum computation, through quantum metrology, to quantum cryptography. Such reconstruction is typically carried out in individual microscopic objects (atoms, ions, photons, Josephson junctions, etc.), which, while intuitive and straightforward, pose experimental challenges due to signal strengths and the complexity of handling the systems (complexity of the experimental apparatuses). A certain alternative to such systems is ensembles of non-interacting objects. In such cases, the absence of interaction enables the description of the ensemble using a single-object approximation and describing it with the collective density matrix. Although the approach is only an approximation, many systems exhibit a range of quantum features (uncertainty-principle-based noise, squeezing, entanglement, etc.) and can be used in some cases for quantum information storage and processing.

A specific example of a system enabling a collective quantum description is isotropic liquids, consisting of molecules with spin-1/2 nuclei, at zero or ultralow magnetic fields (ZULFs). The nuclear state of this system can be monitored by detecting magnetization induced by the sample using, for example, atomic magnetometers. At ZULFs, the evolution of the quantum states in the molecules is predominantly governed by the internal interaction (J coupling), and their energy level structure forms a long-living (> 1 s) energy-level structure that can be selectively addressed by appropriately oriented and modulated magnetic fields. This opens the means for quantum applications of such systems.

During the presentation, we will discuss the theoretical and experimental details of magneto-optically detected ZULF nuclear magnetic resonance (NMR) [1]. The formation of the energy-level structure, remaining that known from atomic physics and based on intuitive principles, will be explained. Next, the ability to induce specific transitions between the levels and means of modifying the generated state will be discussed. Finally, a technique for reconstructing the states through the analysis of the magnetic field generated by the molecules will be shown [2]. This will allow us to present a new experimental system which can be used for quantum information processing and long-lasting storage.

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Towards a High Duty Cycle Transportable 171Yb Lattice Clock

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Advancements in optical clock technology have been ongoing over the past decade, with recent achievements surpassing state-of-the-art microwave clocks by over two orders of magnitude in both stability and total uncertainty. This exceptional frequency control, reaching 18 digits or better, opens up exciting possibilities for various applications in fields such as Fundamental Physics (including tests of Lorentz invariance and the drift of fundamental constants), Astronomy (particularly in the search for dark matter), and Earth Sciences (including Chronometric geodesy).

Transportable optical clocks have drawn a considerable interest in the last years, as they are the only ground-based instrument able to perform a mapping of geopotential variations. A refined knowledge of the geoid (equigeopotential best matching the level of the ocean at rest) is an important aspect of a future redefinition of the second, since it is key to comparing remote clocks. In order to meet this need, SYRTE, Observatoire de Paris, started in 2021 the design and realization of a transportable ytterbium lattice clock based on Yb171. The scientific objective is to develop an instrument that can be connected to some of the ~60 outputs of the French research infrastructure REFIMEVE, a metrological fiber network link that disseminates disseminating a 1542 nm ultrastable carrier throughout the territory. Remote comparisons to the ~12 operational European optical clocks will allow measurements of geopotential changes in space and time.

In this paper, we outline the recent advancements in assembling this portable device, notably the construction of the vacuum system, which will enable us to achieve ultrafast loading of the atoms (target $>10^4$ atoms in <100 ms) to minimize the Dick effect and achieve a duty cycle exceeding 0.5. We will discuss the impact of atomic beam collimation using multi-detunings 2D-optical molasses, aiming to address all transverse velocity classes up to ± 20 m/s. Additionally, we will detail the deceleration accomplished by a Zeeman slower based on permanent magnets, comparing outcomes with prior numerical simulations. Lastly, we will outline the forthcoming construction phases, including a 2D magneto-optical trap and a Science chamber featuring a cavity-formed optical lattice.

Total cross section measurements for low-energy electron scattering on deuterated methane (CD_4) molecule

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A detailed understanding of the effects resulting from the interaction of electrons with deuterated molecules can provide a lot of information about numerous processes occurring in nature. For example the study on dissociative electron attachment to thymine and its deuterated counterpart allowed to demonstrate the selectivity of bond breaking in this DNA-crucial nucleobase [1]. The results on electron-deuterated molecules interaction studies are invaluable also for astrochemistry [2] and isotope effect research [3].
In Figure 1 preliminary results of absolute *grand*-total cross section (TCS) measurements for low-energy (0-300 eV) electron scattering on deuterated methane molecule are shown. The experiment was performed using an electrostatic electron spectrometer [4] operating in the linear transmission mode [5]. The present results are compared with those for regular methane [6].

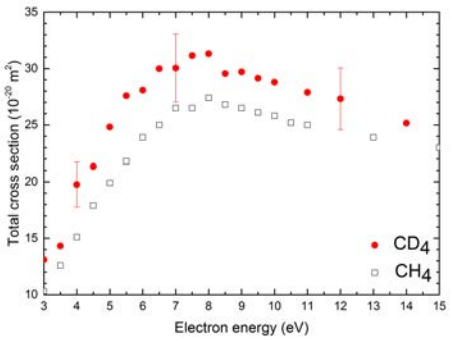

Figure 1: Measured TCS for deuterated methane compared with TCS for regular methane.

Acknowledgement

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Estimation of core-valence and core correlations using the Rayleigh-Schrödinger perturbation theory in an irreducible tensorial form

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We present the combination of the relativistic configuration interaction (RCI) method with the stationary second-order Rayleigh-Schrödinger many-body perturbation theory (RSMBPT) in an irreducible tensorial form method to account for the core-valence (CV) and core (C) correlations [1, 2]. The RSMBPT method allows to estimate the contribution of the CV and C correlations with preferred core and virtual orbitals for any atom or ion. After selecting the most important CV and C correlations, other important correlations are included in the regular way, and followed by the RCI calculations. The developed method has an advantage over the regular method because it allows the selection of the most relevant CV and C correlations and significantly reduces the CSF space. This leads to a smaller matrix and makes it easier to diagonalize. At the same time, it reduces the resources and CPU time required for RCI calculations. This new method was applied to light and moderate complexity ions. Here the comparison for a small part of the calculated energy levels for Fe XV using regular RCI and RCI (RSMBPT) methods together with NIST [3] results is presented in Table 1. During the conference results using RCI (RSMBPT) for Ce III would be presented.

Table 1: The energy levels (in cm^{-1}) and differences (in cm^{-1}) between **CV+C RCI** and NIST energies (ΔE**(CV+C RCI)-(NIST)**), and between **CV+C RCI (RSMBPT)** and **CV+C RCI** energies (ΔE**(CV+C RCI (RSMBPT))-(CV+C RCI)**) for Fe XV are given when CV and C correlations are included in the computations.

No.	State	Energies, cm^{-1}		Energy differences, cm^{-1}					
		NIST	**CV+C RCI**	ΔE**(CV+C RCI)-(NIST)**	ΔE**(CV+C RCI (RSMBPT))-(CV+C RCI)**				
					95%	99%	99.5%	99.95%	100%
1	$3s^2\ {}^1S_0$	0	0.00						
2	$3s3p\ {}^3P^o_0$	233842	233850.17	8.17	40.46	28.59	18.70	0.81	0.08
3	$3s3p\ {}^3P^o_1$	239660	239687.93	7.93	−39.77	−12.42	−8.63	−9.83	0.02
4	$3s3p\ {}^3P^o_2$	253820	253843.34	23.34	−26.07	−8.15	−3.36	−8.36	0.00
5	$3s3p\ {}^1P^o_1$	351911	352122.45	211.45	−52.83	−17.27	−10.19	−9.65	0.03
6	$3p^2\ {}^3P_0$	554524	554680.46	156.46	106.32	28.99	23.29	8.69	0.01
7	$3p^2\ {}^1D_2$	559600	559895.66	295.66	11.77	−1.95	−5.85	−7.92	0.00
8	$3p^2\ {}^3P_1$	564602	564723.10	121.10	69.06	20.94	12.57	−0.04	0.00
9	$3p^2\ {}^3P_2$	581803	581976.83	173.83	−42.00	−20.93	−14.19	−8.90	−0.01
10	$3p^2\ {}^1S_0$	659627	660138.51	511.51	91.24	17.68	12.36	2.60	0.00
	N_{CSFs}		372043		90859	182643	218556	300041	360394

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Exploring N_2^- electronic resonances under nuclear motion

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The XCHEM method[1] allows the study of the metastable state of the anionic molecular nitrogen molecule and its ultrafast autodetachment into neutral molecular nitrogen. At the core of the XCHEM method lies the Gaussian-B-spline basis (GABS)[2], used to represent bound and continuum states. It has been successfully applied to cations, such as neon[2], nitrogen[3] and carbon monoxide[4]. In this communication, we present results for a diatomic anion, the nitrogen anion, at different nuclei positions.

N_2^- resonant state has been thoroughly studied before and extensive data is available. Therefore, this work serves as a benchmark for the usage of this XCHEM formalism in the study of resonances in anionic species, comparing the results with the aforementioned data that is accessible. XCHEM has never been used before in the study of these anionic states, and for future works it is important to assess the validity of this method. In addition, the effect of nuclear motion has been studied by calculating this electronic resonances at different internuclear distances.

The results are in close agreement with the theoretical and experimental data, surpassing several methods in the accuracy of the calculation of the E_R resonant energy and Γ width of this resonant state. These values establish the XCHEM formalism as a valid method for the analysis of these resonant states.

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Atomic and molecular ion studies in the cryogenic ion-beam storage-ring facility, DESIREE

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Cryogenic electrostatic ion-beam storage rings are ideal tools for studies of the intrinsics properties and interactions of atomic and molecular ions as they combine the ability to observe the same ensemble of ions for extended times with the ease of detection of neutral particles by available technologies [1, 2, 3, 4]. DESIREE at Stockholm University is unique in that it consists of two electrostatic rings enabling the studies of interactions between pairs of oppositely charged ions [1, 2]. We present DESIREE and results of fundamental studies of atomic [5], molecular [6] and metal dimer [7] anions, as well as a demonstration of the stability of the small molecular dianion, C_7^{2-}. Furthermore, we present astrophysically motivated studies of polycyclic aromatic hydrocarbons (PAHs) concerning their ability to survive under the conditions of the interstellar medium [9, 10]. While all the above examples make use of only one storage ring and the ability to interact with the ions using lasers, the purpose of the dual-ring construction is to enable low-energy collisions between oppositely charged ions. Atomic mutual neutralization is for example studied for metal ions with negative hydrogen ions to enable the determination of the concentration of the latter in stars from astronomical observations [11]. Very recently, the first results with molecular ions were published where full use of the ability to wait for the ions to relax and then study their mutual neutralization reactions was made [12, 13].

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Towards continuous superradiance for active optical clocks

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Superradiance is a phenomenon that can allow lasing directly from narrow clock transitions. Thanks to this property, steady-state superradiant lasers have been proposed as candidates to realize a new generation of frequency references: active optical clocks [1, 2]. Here we present two approaches of achieving continuous superradiance in different temperature regimes [2, 3]. One approach lends itself to producing simple and compact optical frequency references for a wide range of scientific and industrial applications, while the other challenges the state-of-the-art of short-term frequency standards. The nature of the superradiant phase transition offers many opportunities to study open questions in highly-correlated many body physics.

With our first approach, we reduce the size and complexity of a superradiant laser and explore the appearance of collective behaviour in a thermal beam apparatus. Resonance widths in hot gases of atoms are dominated by Doppler and transit time broadening. We reduce the first effect by the implementation of a slowing and velocity-selection scheme, so that the main requirement for superradiance is a collective linewidth broader than the transit time broadening. Here we use ^{88}Sr atoms crossing the mode of an optical cavity to demonstrate the emergence of a collective behaviour in the form of the well known 'normal-mode-splitting', for $^1S_0$ atoms, and optical gain for an inverted sample in $^3P_1$ [4]. For both conditions we model the spectral properties of the transmission with a mean-field theory and find a good agreement with the experimental observations. This comparison shows the proximity to the superradiant phase transition.

With the second approach, we aim to realize continuous superradiance with an ultracold sample of strontium atoms. We create our continuous source of μK atoms using a method largely based on previous work in our group [5], which involves separating the laser cooling steps in space rather than in time. A new feature is that the atoms will be transported into an optically and magnetically shielded science chamber. There, they will be loaded into a moving magic-wavelength optical lattice oriented along the axis of a high-finesse bowtie cavity, where we plan to generate superradiant emission on the clock line. Thus far, we have realized a continuous broadband "red" magneto-optical trap (MOT) of around 4×10^7 ^{88}Sr atoms and a pulsed single frequency MOT where we can reach sub-microKelvin temperatures. We are also working towards an advanced loading scheme for quasi-continuous long distance transport to create a high flux of μK strontium atoms into the cavity.

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Quantum Monte Carlo study on positron binding to atomic anion dimers

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Recently, it was found that the positronic complex with $(H^-)_2$ can form the stable bound state concerning the dissociation into H^- + PsH by a positron mediate bonding [1]. This bonding situation, which resembles the well-defined single covalent bond, was qualified as “positronic covalent bonding”. On the other hand, a similar binding mechanism may be possible for anion dimers of other alkali species, such as lithium. In this study, we have investigated the stabilities of $[X^-; e^+; X^-]$ homonuclear systems with X = H and Li using the quantum Monte Carlo method combined with the multi-component molecular orbital calculation [2,3].

Figure 1 shows the computational results of potential energy curves (PECs) for $[Li^-; e^+; Li^-]$ against the internuclear separation by the Hartree-Fock (HF), configuration interaction (CI), and diffusion Monte Carlo (DMC) methods. The results show that the system has a single energy minimum in all the PECs, and its internuclear distance is drastically shortened by improving the accuracy of interparticle correlation effects. According to the characteristics of the electron and positron densities, the energy minimum structure at the HF level appears like a positronic covalent bonding, whereas the compact structure predicted at the DMC level may have strongly delocalized characters of both one excess electron and a positron.

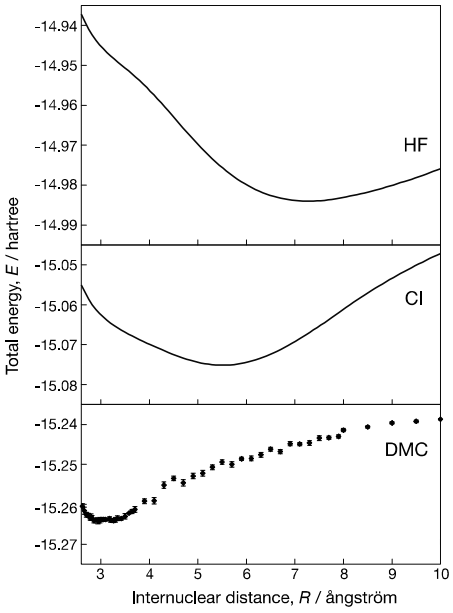

Figure 1. PEC of $[Li^-; e^+; Li^-]$.

By evaluating PECs of both lower energy decays into $Ps + Li_2^-$ and $Ps^- + Li_2$, we confirmed that the $[Li^-; e^+; Li^-]$ system is stable for both these thresholds. The analytical results suggest that the dominant structure is depicted as Ps binding to Li_2 anion, which is different from the $[H^-; e^+; H^-]$ case that has a locally stable covalent positronic bonded structure [1,2,4].

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Robustness of Grover's algorithm with multi-phase matching

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Grover's algorithm was one of the first quantum algorithms and an important milestone that shows to the scientific community the importance of the field of quantum information. This probabilistic algorithm is quadratically faster than its classical counterparts and would have important practical applications. Both reflection operators participating in the algorithm's iteration can be constructed by using generalized Householder reflection.

When the phases are the same in each iteration, the algorithm is called phase matching modification of the algorithm and this can make it deterministic. Numerical calculations show that such construction is robust only if the phases of both reflections are the same.

Multi-phase matching is when the phases used at both operators depends on the iteration number. This modification also can make the algorithm deterministic.

Here we use semi-empirical methods to show that such multi-phase matching construction of the coins greatly increases the robustness of the algorithm. We compare three different multi-phase matching modifications and show that they are much more robust than the phase matching modification. This effect becomes stronger when the two phases in the iteration differ greatly. For more information, see Ref. [1]

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Squeezed Bose-Bose droplets: binding, structure and vortices

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We present the results of the study of ultradilute Bose-Bose liquid droplets squeezed by an external harmonic potential in one spatial direction, recently published in Ref.[1]. Our theoretical study is based on a functional that is built using quantum Monte Carlo results of the bulk phase and incorporates finite-range effects; for comparison we also present results obtained using the Lee-Huang Yang functional in reference cases.

We first focus on a characteristic feature of these drops, the existence of a critical atom number, that is the minimum number of particles to have a many-body bound state. We report how the critical atom numbers for different magnetic fields change with varying confinemment strengths in the direction towards a quasi-two-dimensional setup. By squeezing the droplet beyond the strength used in the experiment [2] we find that the critical atom number decreases approximately linearly with the harmonic oscillator length of the confining potential. For the largest squeezing explored in our work and the strongest interparticle interaction, we predict stable drops at the level of one thousand atoms. The critical numbers obtained with QMC functional for any confinement and applied magnetic field are reduced with respect to the estimations based on the Lee-Huang-Yang model.

Second, we report how size and shape of droplets change with the magnetic field and confinement strength. When the number of atoms in the droplet is close to the critical atom number, they become less flat when the squeezing is increased, which can be understood as a consequence of a confinement-induced interaction strength. When the number of atoms in the drop is much larger than the critical value, we observe saturated drops, which extend perpendiculary to the direction of squeezing when confinement strength is increased, similarly to helium droplets. Obtained central density of drops is higher for the quantum Monte Carlo functional than for the Lee-Huang-Yang one.

Finally, we present our first unpublished results on the study of vortices in droplets with different squeezing strength.

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Electron impact double ionization of krypton

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*E*lectron impact double ionization (EIDI) is a fundamental process in atomic and molecular physics, impacting various fields like plasma physics, laser physics, astrophysics, and physical chemistry. It involves a projectile electron interacting with a target atom/molecule, ejecting two electrons and ionizing the target. Accurately describing EIDI requires sophisticated models capable of calculating the most detailed information on this process: the five differential cross section (FDCS). The FDCS encompasses the ejected electrons' momenta, energies, and angles relative to both the projectile and the outgoing ionized target. This work focuses on employing a refined theoretical framework to investigate the FDCS of Krypton (Kr) atoms [1]. Our model incorporates crucial post-collisional correlations between the ejected electrons [2]and describing them by distorted waves: This approach accounts for their interaction with the residual ion core after the collision. Instead of treating them as free particles, we consider the potential they experience due to the distorted core. This investigation aims to provide a comprehensive understanding of EIDI in Kr atoms through these crucial post-collisional effects. We specifically focus on applying distorted waves to describe the behaviour of the ejected electrons under the influence of the fast-incoming electron (5500 eV). Additionally, our results obtained with the chosen model will be compared with other models that are also based on the first-Born approximation. This comparison will allow us to assess the accuracy and effectiveness of our model in describing EIDI of Kr atoms.

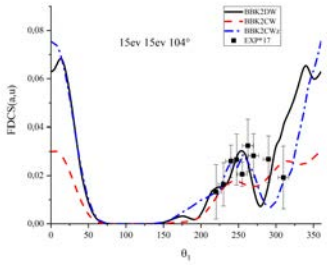

Figure 1: FDCS for the electron impact ionization of Krypton 4p.

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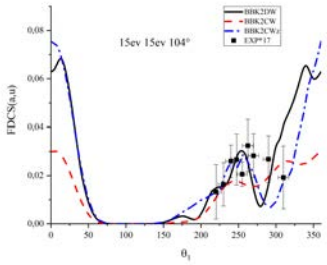

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Enantiomer-specific control of quantum state population of chiral molecules

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Chiral molecules are important in many chemical and biological processes and they are also at the heart of some fundamental physics questions. Recently, enantiomer-specific state transfer (ESST) was experimentally demonstrated [1,2]. Here, the application of three mutually orthogonally polarized microwave fields yields enantiomer-specific population control in a chosen quantum state that is part of a triad of rotational states. In theory, ESST can reach 100% transfer efficiency. However, early studies on ESST reported only modest state-specific enantiomeric enrichment, limited to a few percent. This is primarily due to the thermal population of rotational states and the spatial degeneracy of these states. In our work, we combine ESST with optical methods to overcome the previous limitations on the transfer efficiency. This approach enables quantitative studies of ESST, explicitly including the role of spatial degeneracy [3].

I will present our work where we both experimentally and theoretically investigate the influence of microwave pulse conditions on ESST [4]. Moreover, we recently established near-ideal experimental conditions by depleting two out of three rotational states of a triad prior to ESST using a combination of UV and microwave radiation. I will present data from these experiments, where we demonstrate full control over the population in a chosen rotational state for a given enantiomer [5].

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Interferometry with qudits encoded in nuclear spins in a SU(N≤ 10) Fermi gas

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Atoms with SU(N) symmetry offer a robust platform to encode qudits. ^{87}Sr enables engineering up to d=10 qudit in its ground state. Qudits operate on a larger Hilbert space than qubits, which allows them to perform more complex parallel computations. Qudits also create new possibilities for atom interferometry. Here, I will present a few atom interferometric schemes we demonstrated with ^{87}Sr atoms qudits.

By addressing four nuclear spin states, we can run two Ramsey interferometers parallel to each other in a single interferometric sequence. Our first interferometric sequence probes a direct measurement of two non-commuting observable quantities [1]. The second interferometric sequence measures the tensor and the vector light shifts in a single measurement. In both cases, we start our experiment with a polarized Fermi gas in one of the nuclear spin states of ^{87}Sr. A spin-selective momentum-transfer technique allows us to read the atomic populations of two nuclear spin states in a single measurement [2]. By applying a quadratic light shift in the ground-state manifold, we isolate a system of two nuclear spin states and can drive Rabi oscillations between them. To generate this quadratic light shift, we use π-polarised light whose frequency we tune within the hyperfine splitting of the $^3P_1$ state. This splitting is large ($\sim 2.5GHz$) compared to the linewidth ($\sim 7.4kHz$) of the $^3P_1 \leftrightarrow ^1 S_0$ transition, which allows us to engineer strong tensor light shifts in the ground state. Finally, we create a superposition of four nuclear spin states using a combination of three $\pi/2$ Rabi pulses. With all these elements, we prepare the two interferometric sequences mentioned previously.

The weak coupling of nuclear spins to external magnetic fields ensures qudits with a long coherence time ($\sim$ few seconds). Benefitting from this fact, we perform a test of SU(N) symmetry in the ^{87}Sr ground state, by probing collisionally-dependent phase shift in a standard Ramsey sequence. Our preliminary results set an upper bound to SU(N) asymmetry of $< 0.1\%$.

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The confined helium atom: An information–theoretic approach

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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.).

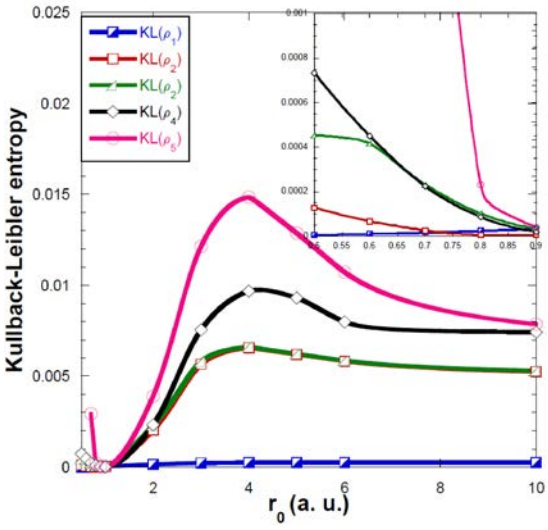

Figure 1: Kullback-Leibler entropy, as a function of the confinement radius r_0, between the uncorrelated wavefunction and each one from a set of wavefunctions with increasing degree of correlation (from Ref. [2]).

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

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Reconfigurable arrays of neutral atoms arranged in individual optical tweezers provide a prospective platform for quantum computing. Nevertheless, the realisation of high-fidelity multi-qubit quantum gates in atomic registers presents an outstanding challenge. Leveraging multi-qubit operations allows to significantly reduce the total gate count for complex quantum algorithms, thus paving a way to the practical applications of near-term NISQ devices.

A promising technique for quantum gates implementation is based on Stark-induced Förster resonances [1, 2]. The external electric field allows to compensate the Förster energy defect between the Rydberg register collective states, leading to a significant interaction enhancement. Thus, Förster resonance transfers enable the gate implementation between strongly distant qubits (with interatomic distances of $\sim 10 - 20$ μm), providing ample opportunities to increase interconnectivity in neutral-atom-based devices.

An extended study of few-body Förster resonances in ordered ensembles of ultracold Rydberg atoms of Rb and Cs has been conducted by our team in Aime Cotton Laboratory. Stark-induced resonance transfers have been numerically demonstrated within a quasi-classical interaction model framework, taking into account finite Rydberg lifetimes, as well as estimating the influence of unwanted transitions. We have designed a number of protocols to implement high-fidelity (up to 99.7%) three-qubit Toffoli and CCPHASE gates [1, 3, 4]. We have also investigated a number of techniques to improve gate stability, including the application of radio-frequency induced Förster resonances [4].

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CARIOQA : a pathfinder for space atom interferometry

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A strong potential for space applications is anticipated from the performances of inertial sensors based of cold atom interferometry on ground. Spatial geodesy missions could benefit from the high level of stability and accuracy demonstrated by these instruments [1]. Mission proposals aiming at testing fundamental laws of physics in space are also based on atomic sensors [2].

Cold atom interferometers are expected to benefit greatly from space environment. Microgravity will cancel the limit on interrogation time set by gravity on Earth, potentially allowing for a gain in sensitivity of several orders of magnitude. However, new scientific and technological challenges have to be overcome to reach the full potential required for future scientific missions.

The CARIOQA [3] project aims at developing a pathfinder in a relatively short timescale, that will pave the way for ambitious space missions based on cold atom interferometry. It will allow to demonstrate key features of space atom interferometry such as seconds long interrogation time and active rotation compensation. In this presentation I will give an overview of the project and describe some of the scientific challenges associated to the adaptation of atom interferometry to orbital space environment.

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Robust molecule quantum gates

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Optically trapped polar molecules, thanks to their tunable long-range electric dipole–dipole interactions and a rich internal structure, are an emerging platform for quantum technologies and for a wide range of quantum science applications. There have already been several proposals on how to realize high-fidelity two-qubit entangling gates [1, 2], but one of the main challenge that these protocols have to face is the sensitivity to variations of experimental parameters such as the molecular distance or the microwave control fields. In this work we address this problem by designing robust molecule quantum gates through quantum optimal control techniques, e.g. GRAPE [3, 4], which have already demonstrated their capabilities of realizing robust and time-optimal gates with neutral atoms [5, 6].

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A cryogenic open-ring Penning trap for laser-based mass spectroscopy

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The current Penning-trap system at the University of Granada built for precision (laser-assisted) mass spectroscopy [1] is based on an open-ring geometry, which allows for laser addressing of the radial modes and fluorescence collection [2, 3]. Although laser-assisted motional-frequency measurements have been performed at room temperature [4], using a cryogenic trap would improve the background pressure (leading to more precise frequency values), reduce the ion heating rate at the ground state of motion, and open the possibility of using quartz resonators [5] in this temperature range.

We have designed a new cryogenic Penning trap that retains the open-ring electrode geometry and improves the mechanical stability, thus enhancing the quadrupolarity of the static electric field. It is an open cryogenic system that allows the injection of ions created in external sources and their extraction towards other regions of the beamline. The trap is thermally anchored to a surrounding can which is connected to the 4 K stage of a cryocooler. Another can at 40 K encloses the system and acts as a radiation shield.

In this contribution, we will present the design guidelines, the vacuum performance simulations, and the results of the first cryogenic tests of the new trap in an ancillary setup. We will also discuss the arrangement of the cryogenic trap in the highly homogeneous 7 T magnetic field.

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The quantum offset of velocity imaging-based electron spectrometry and the electron affinity of As

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Since the advent of 2-dimensional high-resolution electron detectors, 2-D electron imaging has been routinely used for electron spectrometry [1]. When the accelerating electric field and distance are large enough to make the transit time of the electrons to the detector quasi-independent of their initial kinetic energy, the area of the circle that encompasses all classically allowed detection points directly provides a measure of that energy. Referring to this principle, the so-called "slow electron velocity-map imaging" (SEVI) technique has been used extensively to record photoelectron spectra [2] and measure photodetachment thresholds [3].

Even though the principle has no essential flaw, a confusion has been constantly made, however, between the maximum distance at which the electron can reach the detector off-axis, and the radius at which the maximum electron current is observed. In fact, the limit set to the area of the detector that can be reached by an electric field-guided electron is the limit set to the transverse motion of a quantum particle by an effective potential well. In this situation, the electron has indeed a presence-probability maximum close to its "turning point", on the potential wall, but with a finite offset towards the region of positive kinetic energy, inside the potential well. As a consequence, taking the radii of the bright rings that appear on phosphor screen-equipped electron detectors as the radii of maximal transverse offset results in an underestimation of the latter, classical, radii. Worse, the smaller the electron energy, the larger the error, which results in a non-zero offset, when extrapolation of the radii down to zero is used to determine, e.g., a detachment threshold.

The quantitative law of the effect will be given at the conference, together with experimental illustrations, both with ancient photodetachment-microscopy images recorded on O^- [4] and with recent data taken on As^-. The latter make it possible to get a measure the electron affinity of arsenic, numerically ca. 0.80448(1) eV, which appears significantly smaller than the 0.8048(2) eV value last published [5]. However, since this last measurement did not fall back on electron imagery, the discrepancy has probably nothing to do with the quantum offset just discovered.

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Single-particle excitation spectrum of interacting Fermi gases at the fundamental discrete quantum level

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(Dated: May 15, 2024)

Ultracold interacting Fermi gases provide model systems in which to study many-body quantum physics connecting the physics of BCS-superconductivity with that of Bose–Einstein condensates (BECs) [1]. Modern spectroscopy techniques allowed to experimentally measure the single-particle excitation spectrum (SPES) [2, 3], a fundamental property of these systems directly predicted by many-body theories [1]. These theories are essentially Mean-Field theories and Montecarlo simulation methods which, for large number of atoms, do not provide a full description of the SPES at the fundamental discrete quantum level. In this work, we compute the SPES of a Fermi gas in the BEC regime at $T = 0$. Our technique, based on the well known Schmidt decomposition and a many-body theory of correlated pairs, allow us to compute all the single-particle energy levels of the system, as well as the particle momentum and degeneracy associated to these discrete quantum levels. Our results are valid for arbitrary number of atoms and allows to predict future experiments with higher energy resolution spectroscopy.

PACS numbers: 05.30.Fk, 67.85.Lm, 03.75.Hh,

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A Photon-atom interface at telecom wavelengths

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Enabling communication between quantum devices, such as clocks, computers, and simulators has the potential to significantly enhance the capabilities of their applications, such as quantum sensing and computing. The key to achieving this lies in establishing efficient communication channels among these quantum devices even over a long distance, which involves the exchange of qubits encoded in light at telecom wavelengths through optical fibers [1]. In this context, I will present an overview of the new experiment that we are building in Florence, which focuses on interfacing single photons at telecom wavelengths with individual neutral ytterbium atoms trapped in optical tweezers [2, 3]. By leveraging the unique properties of the ytterbium clock state and its telecom transitions, our objective is to interface a long-lived "matter" qubit and resonant light, including atom-resonant heralded single photons or photons forming entangled pairs [4]. I will discuss the first developments, the motivation for exploring this research line and its impact as a crucial foundation for distributing entanglement between light and matter.

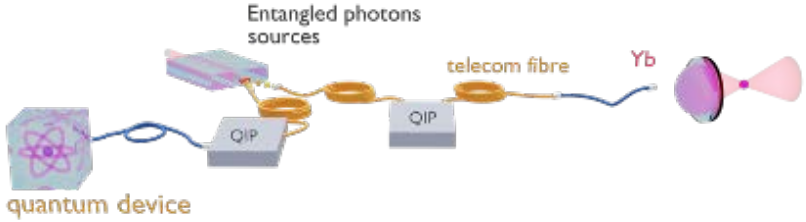

Figure 1: Non-degenerate entangled photons as a resource for interfacing quantum devices with atoms at telecom wavelengths

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Optimisation of a Compact, High-Flux Grating Magneto-Optical Trap (gMOT) Source for Improved Atom Trapping

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Grating Magneto-Optical Traps (gMOTs) have emerged as a pivotal technology in quantum sensing applications, offering a unique approach to atom trapping. However, a notable limitation of conventional gMOTs is their relatively low atom trapping efficiency. This constraint hinders the full potential of quantum sensing applications, which demand a high flux of atoms. Recent advancements in the field have demonstrated that a significant increase in atom capture can be achieved through the implementation of a 2D+ MOT configuration. Building upon this, our current work focuses on the development and optimisation of a compact, high-flux gMOT source. We report here the design considerations, construction methodologies, and preliminary results of our gMOT source. Our findings indicate a substantial improvement in atom trapping efficiency, paving the way for more sensitive and accurate quantum sensing applications. This work not only contributes to the advancement of gMOT technology but also opens new avenues for exploration in quantum technologies.

Simultaneous dispersive interaction of multiple frequency comb lines with a cold atom cloud

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Until now, the linear dispersive regime of light-matter interaction in a cavity using multi-frequency excitation has only been explored theoretically [1]. Recently, there has been a growing interest in optical frequency combs, characterized by a frequency spectrum comprising over 10^5 phase-coherent modes. These combs facilitate the experimental implementation of multi-frequency excitation in optical resonators.

We use the collective light shift to study the simultaneous dispersive interaction between multiple lines of an OFC and cold atoms in an optical cavity. When atoms are loaded into the cavity, the dispersive interaction between atoms and light inside the cavity leads to a shift in the frequency of the cavity modes. Due to this light shift, certain OFC modes couple more effectively to the cavity mode, resulting in increased transmission (sharp peak in Fig. 1a), while others decouple from the cavity mode, leading to decreased transmission (sharp dip in Fig. 1a). To demonstrate the simultaneous interaction with multiple comb modes, we performed an optical heterodyne beat measurement of a transmitted OFC and a cw laser tuned to the atomic resonance. In Fig. 1b, we show the measured beat signals of the cw laser and the nearest 5 OFC modes in a case with and without atoms loaded in the center of the cavity. As observed, when atoms are loaded in the cavity, the transmission of a certain comb modes is increased, while others are decreased or even vanished.

Unveiling the dispersive regime of cold atom interaction with a significant portion of an OFC's spectrum has the potential to massively enhance quantum computational processes [2], as well as extend laser cooling techniques [3], which would have tremendous implications for spectroscopy and chemistry.

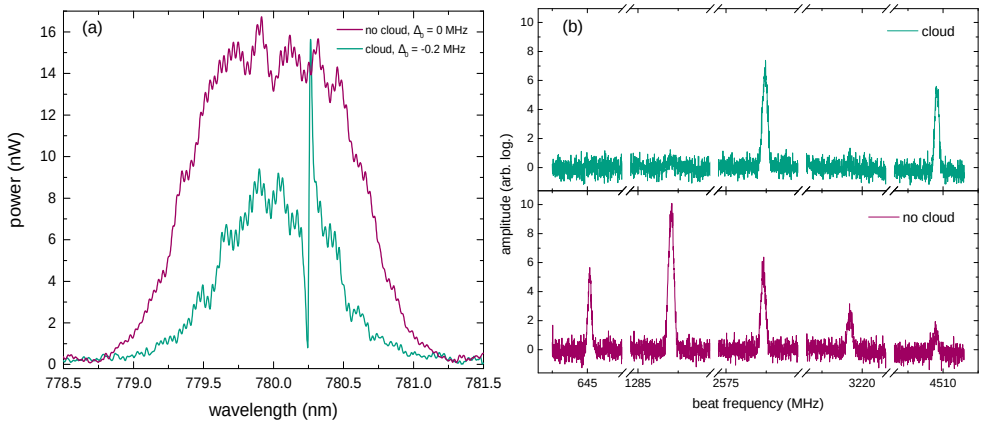

Figure 1: a) The OFC spectrum transmitted through the cavity when the cavity is empty (violet) and when it is filled with rubidium atoms (green). b) Beat signals of the cw laser locked at the $F = 2 \rightarrow F' = 3$ transition and the nearest 5 OFC modes in a case with and without atoms loaded in the center of the cavity.

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Phenomenology of a Rydberg impurity in an ideal Bose Einstein condensate

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We investigate the absorption spectrum of a Rydberg impurity immersed in and interacting with an ideal Bose-Einstein condensate. Here, the impurity-bath interaction can greatly exceed the mean interparticle distance; this discrepancy in length scales challenges the assumptions underlying the universal aspects of impurity atoms in dilute bosonic environments. Our analysis finds three distinct parameter regimes, each characterized by a unique spectral response. In the low-density regime, we find that the Rydberg impurity is dressed by the surrounding bath similarly to the known Bose polaron [1]. Transitioning to intermediate densities, the impurity response, given by sharp quasiparticle peaks, fragments into an intricate pattern bearing the hallmarks of a diverse molecular structure. Finally, at high density, a universal Gaussian response emerges as the statistical nature of the bath dominates its quantum dynamics [2]. We complement this analysis with a study of an ionic impurity, which behaves similarly [3]. Our exploration offers insights into the interplay between interaction range, density, and many-body behavior in impurity systems.

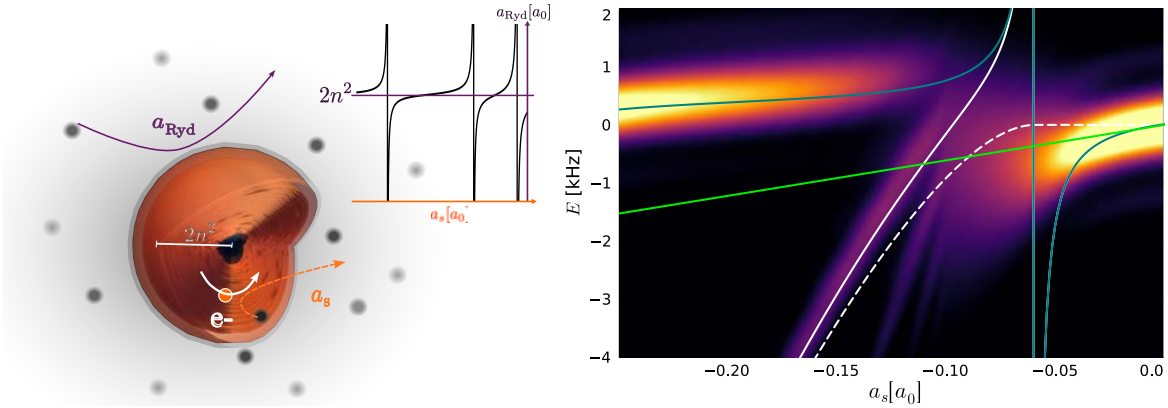

Figure 1: Left: Two scattering lengths characterize the interaction of a Rydberg impurity with its environment. Atoms probing the Rydberg atom's interior collide with the highly excited electron directly; these interactions are characterized by the atom-electron scattering length a_{s}. In contrast, distant atoms interact with the Rydberg atom as a single entity, and the atom-impurity scattering length a_{Ryd} is characteristic of this interaction.
Right: The absorption spectrum $A(\omega)$ of a $50S$ Rydberg impurity in a Bose Einstein condensate with $\rho = 10^{12}\,\mathrm{cm}^{-3}$. Various mean-field results for polaron and molaron energies are overlaid.

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Rovibrational dynamics of Rb_2 in a centrifuge pulse

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In an optical centrifuge laser pulse, polarization axis rotates in an accerated way around its propagation axis. It has been demonstrated that the use of these pulses allows the creation of highly excited rotational states [1]. In this context, we study the rovibrational dynamics of a Rb_2 molecule within the electronic state $^3\Sigma^+$ in the electric field of an optical centrifuge. Time-dependent Schrödinger equation of the system is solved by considering a time profile similar to the experimental optical centrifuge used by the group of V. Milner [2]. We compare these results with the ones obtained by using a gaussian pulse whose spectrum has the same FWHM (2.63 ps^{-1}) and energy as the optical centrifuge. For the latter to happen, peak intensity of the gaussian must be 24.05 times the centrifuge one.

The results show that a large amount of population transfers to different vibrational bands, which makes the rigid rotor approximation no longer valid for those field regimes. Specially, for the gaussian pulse, this transference is significantly greater, and rotational excitation is also slightly greater. Regarding the rotational excitation, the optical centrifuge is more efficient in intermediate and upper vibrational bands ($\nu_0 \gtrsim 12$) than the gaussian pulse for strong fields. Another important effect is the dissociation of the molecule, which is normally larger for the gaussian pulse. For instance, a gaussian pulse with peak intensity 10^{12} W/cm^2 provokes a dissociation of $\sim 15\%$ for the initial vibrational band $\nu_0 = 20$, while for an optical centrifuge with the same energy is $< 0.1\%$. Thus, it seems that the gaussian pulse is transferring population to many different states, whereas the optical centrifuge is more efficient for rotational excitations. For a thermal sample of molecules, the distribution of rotational states presents a pronounced maximum at large excitations for both pulses, showing their efficiency to transfer population to highly excited rotational states.

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Implementation of optimal control methods and top-hat beam for Bragg transition gravi-gradiometer.

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Inertial sensors based on cold atom interferometry are one of the most mature quantum technologies today and can achieve sensitivities that rival conventional sensors [1]. In the field of onboard sensing, differential quantum gravimeters (gravi-gradiometer) are a good alternative to hybrid classical/quantum sensors to reject common mode vibrations and laser phase noises. Our gravi-gradiometer employs a dual source of ^{87}Rb atoms, vertically separated by 1 m, and provides simultaneous measurement of the gravitational acceleration and its vertical gradient using a Mach-Zender-like interferometric sequence [2] [3].

In order to increase the sensitivity (scale factor) of the interferometer, we implement large momentum transfer (LMT) atom-optics via multi-photon Bragg transitions (diffraction order n). However, the efficiency of the large-n Bragg transitions is compromised by the presence of parasitic diffraction orders, and limited by the dispersion of atomic clouds coupled to the laser beam intensity inhomogeneities.

Here, we use an optimal control theory (OCT) algorithm based on GRAPE method to generate dedicated laser phase evolution patterns during the interrogation pulses, for enhancing the fidelity of n=3 (6hk) Bragg atom-optics. It results in a relative increase of contrast of 25% for short interrogation time interferometers ($T = 1$ ms) on both clouds, with respect to no-OCT case, in a regime of suppressed parasitic interferometric loops. Additionally, we demonstrate a sensitivity gain of up to 50% compared to the conventional (n=1, 2hk) atom interferometer with T=1ms. However, further research is needed to extend this to larger T regimes, evaluate and suppress associated systematic bias phase shifts.

Moreover, to address the limitation due to atom-light coupling inhomogeneities across the Gaussian laser beam, we explore advanced optical beam-shaping techniques for implementing flat-intensity beam profiles (TopShape by asphericon) [4]. We demonstrate an associated two-fold increase in contrast for a long time-of-flight (high inertial sensitivity) interferometers of $T \simeq 250$ ms.

The combination of the OCT methods and the top-shape laser beams may allow us to overcome main limitations of the multi-photon atom optics and advance the state-of-the art [5] of quantum inertial sensing.

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Similarity of the near-threshold cross sections for positronium formation and photoionization in polyatomic molecules

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This work reveals a remarkable similarity between the near-threshold energy dependence of the positronium (Ps) formation and photoionisation cross sections for several polyatomic molecules.

Positronium is the bound state of a positron and an electron. It can be formed in low-energy positron collisions with atoms or molecules. Here, the Ps-formation cross sections for aniline ($C_6H_5NH_2$), pyridine (C_5H_5N), and cyclopentane (C_5H_{10}) have been measured using a high resolution ($\sim$35 meV FWHM) trap-based positron beam. The measurements cover the range of energies within a few eV of the Ps-formation threshold, $E_{\rm thr} = E_I - |E_{\rm Ps}|$, where E_I is the target ionisation energy, and $E_{\rm Ps} = -6.8$ eV is the Ps ground-state energy. For pyridine, the magnitude of the cross section is in agreement with earlier low-resolution data [1].

The Ps-formation cross sections are compared with measured photoionisation cross sections shifted to the Ps-formation threshold, with magnitudes scaled by a constant factor. We demonstrate that for each molecule, the two cross sections have a nearly identical dependence on the excess energy within 1–2 eV of the threshold. This similarity is contrary to the significant difference between the two processes. In Ps formation, the interaction between the slow Ps and the residual cation is of short range, and the cross section is expected to obey the Wigner threshold law $\sigma \propto (E - E_{\rm thr})^{1/2}$ (though its validity is usually limited to a very narrow energy range near threshold). In photoionisation, the electron moves in the attractive Coulomb field of the ion, and the cross section must have a step-like onset with $\sigma = {\rm const}$ at threshold. The two processes also involve different constraints, e.g., conservation of the angular momentum vs. the dipole selection rules.

We discuss possible reasons for this similarity. In particular, it appears that the observed near-threshold behaviour is governed by vibrational excitations of the molecular cation and Franck-Condon factors, rather than the energy dependence of the underlying leptonic cross sections. For pyridine, this explanation is supported by a direct comparison with high-quality theoretical data for the vibronic excitation spectrum intensities [2]. We also discuss where the similarity breaks down and in what other targets it can be expected.

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Quantum control of continuous systems via nonharmonic potential modulation

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The preparation of a continuous-variable system in a non-Gaussian quantum state is of paramount importance in various aspects of quantum science. The generation of non-Gaussian states requires a nonlinear resource, often introduced through coupling to an auxiliary degree of freedom, such as a two-level system. On the other hand, some continuous-variable systems already possess intrinsic nonlinearity in the potential of a canonical variable. These nonharmonicites in the potential are typically used to define a qubit within continuous-variable systems. In contrast, we explore methods for utilizing this intrinsic nonlinearity to generate and control states beyond the two-dimensional subspace.

Specifically, we present a theoretical proposal for preparing and manipulating a state of a single continuous-variable degree of freedom confined to a nonharmonic potential [1]. By utilizing optimally controlled modulation of the potential's position and depth, we demonstrate the generation of non-Gaussian states, including Fock, Gottesman-Kitaev-Preskill, multi-legged-cat, and cubic-phase states, as well as the implementation of arbitrary unitaries within a selected two-level subspace. Additionally, we propose protocols for single-shot orthogonal state discrimination and algorithmic cooling and analyze the robustness of this control scheme against noise. Since all the presented protocols rely solely on the precise modulation of the effective nonharmonic potential landscape, they are relevant to several experiments with continuous-variable systems, including the motion of a single particle in an optical tweezer or lattice, or current in circuit quantum electrodynamics. Moreover, the proposed protocols can be utilized in systems with very weak nonharmonicities, e.g., levitated nanoparticles.

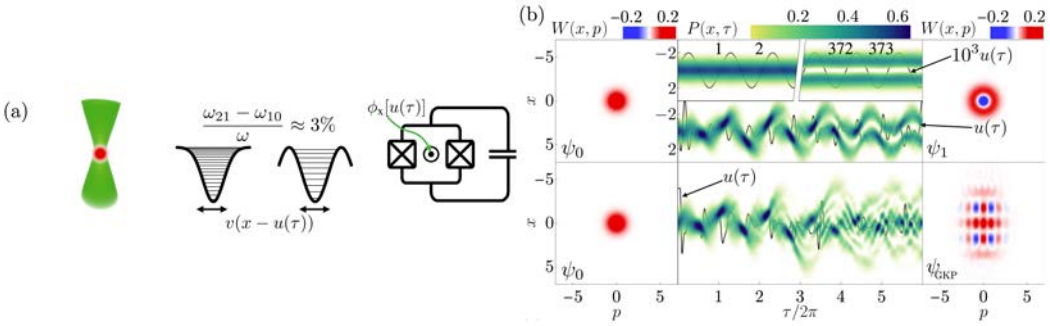

Figure 1: (a) Examples of systems that can be optimally controlled without the need of auxiliary systems—single atoms in optical tweezers and flux-tunable transmons. (b) Time-evolved probability density during the state preparation with the snapshots of Wigner functions. The potential's controlled position is depicted via a solid black line. The top panel shows a comparison between sinusoidal drive resonant with the ground-first excited state transition and an optimized much faster control. The bottom panel presents an optimal control leading to the GKP state.

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Optical tweezer arrays of erbium atoms for quantum simulation

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Neutral atoms in optical tweezers offer great promise as a platform for quantum simulation and computation, with the ability of implementing arbitrary geometries, dynamical reconfiguration and controllable long-range coupling via Rydberg-mediated interactions [1,2]. In this context, the high complexity of lanthanides (e.g., erbium) leads to a rich plethora of optical transition for efficient laser cooling and quantum state preparation [3]. This translates into excellent prospects for their employment on quantum operations by giving rise to magic conditions [4], narrow-linewidth transitions and the ability of trapping Rydberg states.

We present here our results on the successful loading and detection of single atoms of erbium trapped in a linear array of optical tweezers. In our experiment, single atoms detection is accomplished by two complementary techniques: a narrow-linewidth imaging for non-destructive atom detection and a broad-linewidth ultrafast imaging. To achieve single atom occupancies, we characterized the differential light shift for the intercombination line of erbium, and we investigated the light-assisted collisions (LAC) and heating-induced loss processes. In addition, in a previous study, we have started by setting up a survey where we successfully identified and characterized roughly 550 Rydberg states [5], including a direct excitation to an ng-state enabled by the submerged, 4f-shell of erbium. Combined with the single-atom preparation technique, we plan to explore the possibilities of different excitation pathways to high angular momentum Rydberg states, exploiting their properties for the realization of a quantum simulator of erbium atoms in optical tweezers.

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Kinetics of stepwise hydrogen adsorption by size-selected nickel cluster anions under cryo conditions

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We present the H_2 cryo adsorption kinetics of size-selected gas-phase anionic nickel clusters Ni_n^- (n = 9 – 25) under isothermal conditions at 17 K by Fourier Transform Ion Cyclotron Resonance (FT-ICR) mass spectrometry. This contribution continues and extends previous work on N_2 adsorption and activation by isolated transition metal clusters [1, 2, 3]. The kinetic fits [4] reveal cluster size-dependent successive uptake of hydrogen up to saturation. The maximum number of adsorbed hydrogen molecules m_{max} was found to scale with cluster size despite a diminished uptake in the regions n = 15 – 17 and n = 23 – 25. In some cases, the kinetic data reveal intermittent adsorption limits m_x, which imply inequivalent binding sites on the clusters and thus a rough cluster surface [5]. Significant hydrogen desorption at high H_2 coverage occur for several cluster anions indicating molecular adsorption of hydrogen following multiple dissociative adsorption steps. For small clusters, n = 11 – 14, the intensity of the bare cluster (n,0) and subsequent early products decay non-linearly, which is attributed to the coexistence of more than one cluster geometry. We report on the special cases of Ni_9^-, which seems to be entirely inert towards H_2 uptake, and $Ni_{16}(H_2)_m^-$, whose stepwise hydrogen uptake is strikingly influenced by continuous desorption steps, and which reaches saturation upon adsorption of considerably less hydrogen molecules (m_{max} = 6) than any other reactive cluster investigated in this work. Larger clusters repetitively reveal evidence for adsorbate-induced structure change, presumably occupying edge and face sites on the cluster surface. Our current work prepares subsequent kinetic and spectroscopic studies of H_2 adsorbate complexes and of N_2-H_2 co-adsorption.

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Optimisation of Pulse Shapes for Atomic Quantum Memories

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Quantum memories are an integral component in the development of future quantum technologies. They enable quantum repeaters [1], which are pivotal for large scale quantum networks and quantum communication [2], as well as storage of quantum information for the duration of a quantum computational process [3]. One platform for producing such quantum memories are ensembles of atoms.

This work explores the inherent complexity in achieving high performance in atomic quantum memories. Specifically, we use an extension of the Off-Resonant Cascade Absorption (ORCA) protocol [4] adding a dressed state to the system which aims to increase storage lifetimes. This has the potential to decrease the effect of Doppler broadening [5], which remains the primary contributor to current low storage lifetimes.

Here, progress is presented on the optimisation of control pulse shapes for the storage and retrieval processes. The pulses must be optimised with respect to both storage lifetime and overall efficiency of the memory. However, the ability to simultaneously satisfy both constraints is an ongoing challenge, particularly with respect to the required parameter space of the controls. In addition, ensuring the system performance remains robust to both control and environmental fluctuations is vital when modelling these complex systems.

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Stopping power of laser-cooled ion clouds: Application to macromolecule detection

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The GiantMol experiment aims to develop a non-destructive detection method for charged macromolecules using laser-cooled ion clouds in radiofrequency traps. This novel approach relies on modifying the thermal equilibrium of a laser-cooled trapped ion cloud when traversed by a massive charged projectile. The objective is to detect the projectile by measuring the variation in the cloud fluorescence rate. For certain trapping parameters, numerical simulations have shown a detection efficiency of 100% for projectiles with masses exceeding 1 MDa [1]. However, this efficiency needs experimental confirmation.

The macromolecules are generated from an electrospray ionization source. Guiding ion optics are used to limit the dispersion in mass, charge, and energy of the ions [2]. Macromolecules with average masses ranging from 10^3 to 10^6 Da are injected into the target ion cloud composed of $^{40}Ca^+$ ions. This detection method overcomes the limitations of traditional detection devices such as electron multipliers or MCPs for masses exceeding 10^4 Da [3, 4], thus opening new perspectives for mass spectrometry in analytical chemistry by enabling the detection of complex and massive molecules while avoiding their denaturation. Control of the target ion cloud relies on a balance between laser cooling and RF heating of the trap. Trapping parameters are optimized to emphasize this heating after the disturbance caused by the molecule passage [5].

Concurrently, the GiantMol experiment focuses on studying ion stopping power in strongly coupled plasmas. Numerical simulations aim to understand the respective roles of binary collisions and interactions with the plasma. This analysis of stopping power will provide crucial insights into ion-plasma interaction processes and contribute to advancing knowledge in this field.

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The PI-LIST: High-Resolution Crossed-Beams Laser Spectroscopy inside the ISOLDE Laser Ion Source

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Laser resonance ionization spectroscopy in the ion source coupled directly to the isotope production target has been proven to be a highly sensitive tool for nuclear structure investigations on isotopes with low production and extraction yields [1]. While the efficiency of this technique is unrivalled, the spectral resolution is ultimately limited by Doppler broadening. At the ion source temperature of 2000 °C typically required for efficient operation, Doppler broadening results in a 1-10 GHz experimental resolution limit whereas precise measurements of nuclear magnetic and quadrupole moments often require resolving hyperfine structure splittings below the GHz regime. A new laser ion source design has been implemented at ISOLDE recently to provide in-source spectroscopy capabilities down to experimental linewidths of 100 – 200 MHz, an order of magnitude below usual limitations. It is based on the high beam purity Laser Ion Source and Trap (LIST) [2, 3], featuring spatial separation of the hot cavity where potential ion beam contamination can arise from non-laser related ionization mechanisms such as surface ionization, and a clean laser-atom interaction region in an RFQ unit directly downstream, where solely element-selective laser ionization takes place. In the so-called Perpendicularly Illuminated LIST (PI-LIST) [4], a crossed laser/atom beam geometry reduces the effective Doppler broadening by addressing only the transversal velocity components of the effusing atom ensemble. Following the integration of this device as the standard tool for high-resolution spectroscopy applications at the off-line mass separator facility at Mainz University [5, 6], we present its first on-line application at ISOLDE for nuclear structure investigations. Neutron-rich actinium isotopes in the region of assumed octupole deformation were probed, pinning down predictions of recent Energy Density Functional nuclear theories that incorporate reflection symmetry breaking [7]. The applicability of this technique to ISOL facilities in general, its limits especially in terms of significant efficiency loss, and technical implementation challenges are discussed.

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Method for exact gravity compensation in a linear horizontal macroscopic Paul trap

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Paul traps, or quadrupole traps, are used to confine from single to thousands of ions using time-varying electric fields. When the ions are laser-cooled, they organise themselves into an ordered structure from chains to Coulomb crystals [3]. Laser cooled trapped ions are known to be one of the best systems for frequency metrology [1], quantum information [2] and quantum simulation [4].
Macroscopic linear Paul traps have been used to create Coulomb crystals of micrometer-sized particles and to characterise their individual properties at atmospheric pressure [5]. The friction induced by the collisions with the air molecules plays the role of the radiation pressure force of laser cooling. Due to their non-negligible mass compared to ions, the particles are confined typically 2mm below the line of the potential minimum, generating excess micro-motion which can be harmful to the stability of the crystals. In this work, we propose an experimental method in order to determine a potential that compensates exactly for gravity and brings back the particles to the null of the oscillating electric field.
The trapping device used in this work consists of four horizontal cylindrical rods used for radial confinement (with an oscillating voltage of amplitude V_{ac} and frequency $\Omega/2\pi$=50Hz) and two endcap DC electrodes providing a static axial confinement. A parallel additional rod placed below the trap is used to apply a static potential V_g to compensate for the weight of the trapped particles. Macro-particles used in this trap are "3M glass bubbles" with few micrometers size and about 10^{-8}kg weight. They are illuminated by a red diode laser along the trap axis through holes in DC electrodes. The scattered photons are collected by a Nikon D3300 camera. The camera is positioned perpendicular to the trap and on the same horizontal plane as the trapped particles.
To use this system as a testbed for self-organisation of charged particles in various trapping geometries, the value of the voltage V_g that compensates for the weight of the particle needs to be experimentally determined. For a sample based on a few trapped particles organised as a chain along the trap axis, the exact gravity compensation is reached when their vertical positions no longer depend on the amplitude of the confinement voltage V_{ac}. With a single confined particle, we can measure its vertical position as a function of V_g for several amplitudes V_{ac} and deduce the potential that effectively compensates gravity. It is then possible to identify the corresponding position inside the trap for further image analysis.

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Two-photon optical shielding of collisions between ultracold polar molecules

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The growing availability of quantum gases of ultracold polar molecules in several labs revealed a very peculiar situation in the context of few-body physics: At ultracold energies, two such molecules in their absolute ground level, i.e., in the lowest rovibrational and hyperfine level of their electronic ground state collide with a universal collisional rate, even if they have no inelastic or reactive energetically allowed channels, so they leave the molecular trap with a short characteristic time.

Several protocols have been designed, where molecules would simply not reach short distances in the course of their collision by using external fields to modify their long-range interaction (LRI) to shield their collisions.

We propose a method to engineer repulsive long-range interactions between ultracold ground-state molecules using optical fields, thus preventing short-range collisional losses[1]. It maps the microwave coupling [3, 4] recently used for collisional shielding onto a two-photon transition and takes advantage of optical control techniques. In contrast to one-photon optical shielding [2], this scheme avoids heating of the molecular gas due to photon scattering. The proposed protocol, exemplified for bosonic ^{23}Na^{39}K, should be applicable to a large class of polar diatomic molecules.

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Towards Non-demolition Readout of Circular Rydberg States in Calcium

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Because of their long lifetimes, circular Rydberg atoms are a promising tool for quantum technologies [1, 2]. In alkaline-earth circular Rydberg atoms, the Coulomb interaction between the Rydberg electron and the core has been exploited to optically control circular states, thereby extending the experimental toolbox for Rydberg atoms [3]. It has been proposed that this interaction can be harnessed for site selective, non-demolition readout of alkaline-earth circular Rydberg atoms trapped in optical tweezers [4]. We are working on implementing this proposal in calcium, which is an attractive candidate due to its narrow line transition. To trap individual atoms in optical tweezers, temperatures as low as few microkelvin are desirable. The absence of hyperfine structure in alkaline-earth atoms preclude the use of standard sub-Doppler schemes developed with alkali atoms. We present here the latest results of our two-photon scheme to cool calcium atoms below the Doppler temperature [5]. Moreover, we outline the progress and future plans for optical trapping of ground- and circular Rydberg states.

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Towards Li-Yb$^+$ Feschbach resonance

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Feshbach resonances in cold atomic physics are used to tune the interactions between neutral atoms, enabling the construction of quantum simulators with full control over the interaction strength. For atom-ion systems, the existence of Feshbach resonances was observed for the first time between a Ba^+ ion and Li atoms by the group of Prof. Schaetz [1]. However, it has become clear that spin-nonconserving atom-ion collision complicates the use of Feshbach resonances [2]. This adverse effect is caused by second-order spin-orbit coupling in the atom-ion collision. We may expect this effect to be smaller in Yb^+/Li due to the larger spread in energy levels. We will present the upgraded experimental apparatus for combining of Li atoms with Yb^+ ion and the project's progress on studying the atom-ion Feshbach resonance.

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Analyzing Crosstalk Using Optimal Control Methods

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Crosstalk presents a fundamental challenge for various modern quantum computing platforms and can lead to nonlocal errors. Diagnosing and understanding crosstalk is crucial not only to mitigate resulting errors but also to help design robust architectures. Here, we employ optimal control methods, used for creating perfect entangling gates, for detecting crosstalk. This enables us to detect crosstalk for various qubit parameter ranges and analyze the mechanisms causing it. We focus on fixed-frequency transmons which are coupled via a parametrically controlled tunable bus. For this system, we identify different types of crosstalk, some of which we find to be correctable. To this end, we employ optimal control to obtain simple variations of the existing two-qubit protocol. This approach results in a wider range of qubit parameters that exhibit low crosstalk, while still utilizing experimentally feasible protocols.

Mass determinations of Pb-208 and U-238 and observation of a metastable electronic state

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The high-precision Penning-trap mass spectrometer PENTATRAP [1], located at the Max Planck Institute for Nuclear Physics in Heidelberg, features a stack of five Penning traps and determines mass-ratios with a relative uncertainty at a few 10^{-12}. Mass-ratio determinations of stable and long-lived highly charged ions at this level have numerous applications, among others, in bound-state QED, nuclear physics, and the search of possible clock transitions in highly charged ions (HCI) [2]. The features of the experiment, necessary to achieve this precision, include access to HCI provided by two external electron beam ion traps, a 7 T magnet stabilized against environmental parameters, and a cryogenic detection system with single ion phase sensitivity. This is achieved by Fourier Transform Ion Cyclotron Resonance (FT-ICR) detection of the image-current induced in the trap electrodes. These features combined with precisely investigated systematic effects led to our recent measurements of the mass of lead-208 and uranium-238 at a relative uncertainty of 7×10^{-11}. In $^{208}Pb^{41+}$, a long-lived metastable electronic state of around 30 eV was detected.

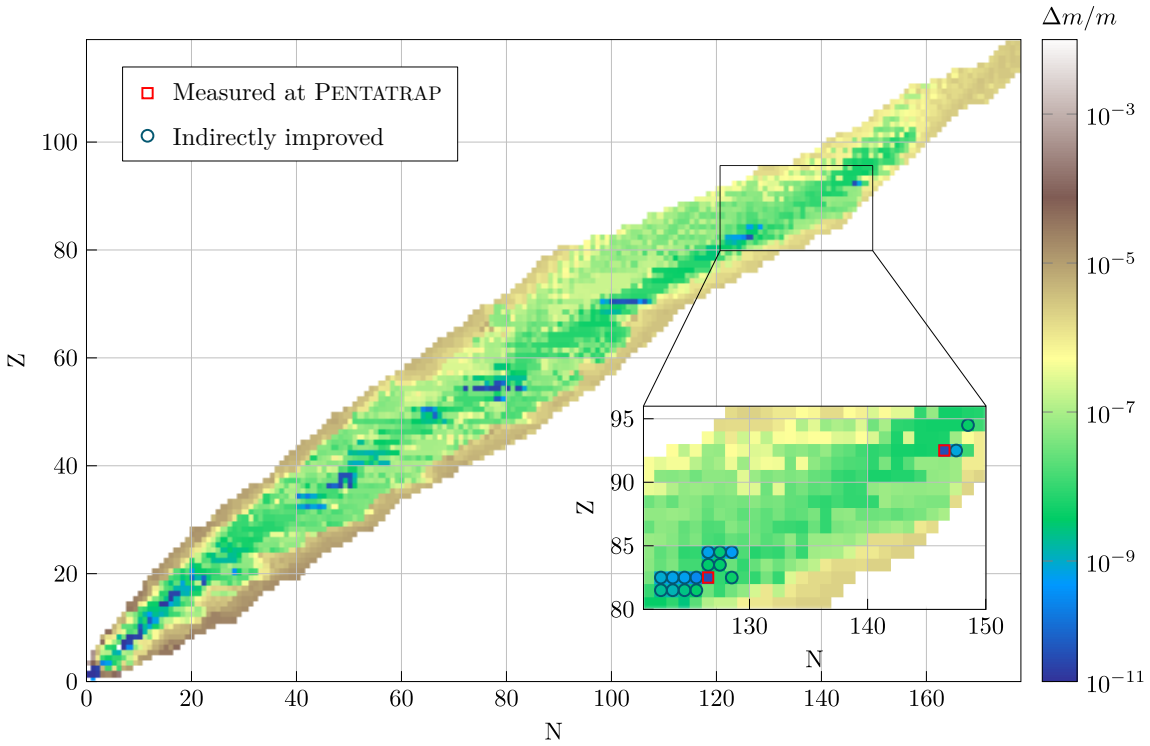

Figure 1: The nuclide chart indicating by color the mass precision of all nuclides that are listed in the AME2020 [3] and the masses measured or indirectly improved with mass determinations at PENTATRAP.

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Towards tuneable "coupling efficiency" of a single atom using a pump-probe scheme

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We propose an experimental implementation of a scheme proposed by Goncalves et al. [1], to produce unusual and tunable photon correlations by interfering resonance fluorescence from a single atom with probe light from a weak laser beam. A number of interesting and potentially useful features are predicted by Goncalves et al., including (under different conditions of pump-probe relative phase and power) the complete extinction of the probe, amplification of the probe, and generation of extremes of anti-bunching and bunching, i.e., $g^{(2)}$ approaching zero or infinity. Interestingly, the expressions for the transmitted power and $g^{(2)}$ can be given in terms of a single parameter, an effective interaction efficiency, suggesting that interference can be used to make up for geometrical and technical limitations on the coupling to single atoms.

We will present the current state of the experimental implementation, using a single atom far-of-resonance trap in a "Maltese cross" geometry system of four high numerical aperture lenses [2] and recent experimental results, as well as the technical considerations we made in order to implement it, including: choice of beam geometry, to minimise the the effects of atomic motion, pump and probe polarisation, optical pumping and coherent population trapping induced by the pump and probe beams, atom heating and methods to mitigate it.

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Cavity enhanced chiral optical rotation

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Chiral sensing plays a crucial role in numerous fields of science and industry. The measurement of weak chiral signals is limited by spurious birefringence, as well as slow and imperfect background subtraction procedures. We present a novel chiral cavity-enhanced polarimeter (CCP), an optical instrument in which the sensing light traverses the chiral sample multiple times, thus amplifying the weak chiral optical rotation signal by the number of cavity round-trips (typically more than 100). The hallmark of this technique is the implementation of rapid signal reversals, which eliminate the need for background subtractions, and enable absolute chiral measurements even in noisy environments, resulting in greatly enhanced sensitivities (0.004 mdeg $Hz^{-1/2}$), relative to commercial instruments (5 mdeg $Hz^{-1/2}$). Finally, we determined the optical activity of the vibrationally chiral 1d-Ethylbenze-(+)-(R) and 2d-Heptane-(–)-(R) due to breakdown of Born-Oppenheimer approximation, in a very good agreement with theoretical calculations.

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

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Ultralong-range Cs-RbCs Rydberg molecule: non-adiabaticity of dipole moments

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Triatomic ultra-long Rydberg molecules are formed by the interaction of a Rydberg atom, an excited atom with an electron with high principal quantum number, and a polar molecule. The study of Rydberg molecules is motivated by its interesting properties [1, 2, 3], and possible applications in ultracold chemical reactions [4] or quantum simulations [5]. In this work [6], we investigate the electronic structure and properties of the Rydberg molecule Cs-RbCs. A complete study of the adiabatic electronic potentials has been performed. The rovibrational structure is described beyond the Born-Oppenheimer approximation, and the coupled Schrödinger equation is solved by including the non-adiabatic coupling terms of the neighbouring electronic potential curves. We explore the transition probabilities through the avoided crossing in the electronic structure, which characterize the ultracold chemical reaction of the Rydberg atom with the diatomic molecule. For the vibrational bound state, we provide the electric dipole moment and decay rates. For the experimental guidance, we identify the best states for photoassociation of this Rydberg molecules and provide the Franck-Condon factors.

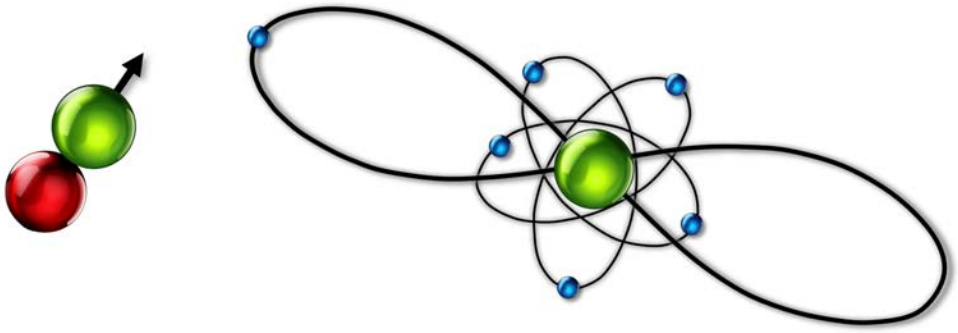

Figure 1: Illustrative sketch of the triatomic ultra-long Rydberg molecule.

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Interacting particles system inside a conducting cavity

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The interaction of atomic species with nanostructures is a subject of great interest because of its different applications. In the context of quantum confinement of atomic and molecular systems, several studies addressed the question of how the spatial limitation modifies their properties [1, 2]; this, in turn, may for example help in exploiting new clean energy sources like hydrogen [3, 4] or improving solar cells by using adapted semiconductors [5, 6]. In these applications, the presence of different materials influences the interaction of the particles of the systems: owing to the dielectric mismatch several effects, difficult to describe and often neglected, may arise.

In this work we are interested in investigating the interaction of a system of charged particles in a cavity inside a conductor. We do this by considering the full potential obtained recently by means of direct integration of the electrostatic energy density [7]. For this geometrical configuration, it was shown that the potential may be written analytically, and contains one and two-body contributions. As a first application, we study here the orbitals (energy levels and wave functions) of a one and two-electron atom placed in the center of a conducting cavity, and analyse the influence of the different potential terms. Our results show that the one-body contributions, which arise from the interaction of each particle with the polarization charge induced on the conducting surface, have a greater effect on the energy levels and the charge density of each state than the electrostatic pair interaction between charges caused by the induced polarization distributions. Moreover, depending on the system, probability densities can be attracted by the conducting surface. In a second investigation, the atom is still placed in the cavity but not in its center. This changes the geometry, and the loss of central symmetry further modifies the interaction, and consequently the atomic energy levels.

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Coherent control of Nitrogen-Vacancy colour defects in diamond

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Quantum sensors form a field of the so-called quantum technologies focused on the measurement of physical properties with high precision. A highly promising technological platform for the development of this discipline is the nitrogen-vacancy colour defect in diamond (NV center), which allows stable measurements of its electronic spin at room temperature. This remarkable feature enables the measurement of external nuclei spins, which forms the basis of nuclear magnetic resonances, by certain excitation protocols. We report the construction of a laboratory based on this technology capable of coherently controlling the quantum state of NV centers through pulsed protocols. We first show the detection of colour defects through a home-made confocal microscope as well as their identification as NV centers by means of pulsed Optically Detected Magnetic Resonances (pulsed ODMR). We then show the coherent control of its state by inducing Rabi oscillations which help us characterize the strength of the microwave field applied to the surface of the diamond. These Rabi oscillations established the basis for more complicated coherence time measurements like Hahn-Echo protocols and relaxation measurements. We also report the successful alignment of a magnetic field through the NV [111] axis studying the symmetry of its ODMR dips under the Zeeman effect. In addition, we report the progress achieved so far with the detection of external nuclear spins through dynamical decoupling sequences. We start with hydrogen spins present in the microscope's objective oil and aim to move into more complex signals inside microfluidic channels.

The impact of RF amplitude on magneto-optical signals in atomic Cs with linearly polarized excitation

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We performed optical-RF double resonance experiments on the Cs D_1 line. We studied experimentally and theoretically how the magneto-optical absorption signals change when subjected to a radio frequency field as the magnetic field is scanned. Although usually these signals are obtained with circularly polarized excitation we used linearly polarized excitation [1]. When atoms absorb weak resonant linearly polarized laser light ($\mathbf{E_p}$) angular momentum alignment is created in the ground state. If, additionally, an external magnetic field is applied along the quantization axis (assumed here to be parallel to $\mathbf{E_p}$), the energies of the magnetic sublevels shift according to the Zeeman effect. As long as the initial alignment is longitudinal (i.e., along the magnetic field axis) this leads to little change in the absorption signal. But if one applies also a single frequency radio B-field (RF) that is oscillating in a plane perpendicular to the quantization axis (see Fig.1 (a)), a decrease in the transmission signal can be observed. This decrease in the transmission signal happens when the radio frequency matches the splitting of the magnetic sublevels. When this happens the radio frequency field couples two adjacent magnetic sublevels that originate from the same hyperfine level and the population is transferred to magnetic sublevels that have a larger transition probability. This leads to an increase in absorption and, consequently, to a decrease in the transmission signal.

First we experimentally observed the dependence of magneto-optical transmission signals on radio frequency value and radio frequency amplitude. Next, we observed the influence of laser frequency, laser intensity and laser beam diameter on the transmission signals. The results show that these signals are strongly influenced by the amplitude of RF as an additional narrow feature appears in the center of the resonance peak for larger RF amplitude values (see Fig.1 (b)).

We acknowledge the support from the Latvian Council of Science, project No. lzp-2020/1-0180: ”Compact 3-D magnetometry in Cs atomic vapor at room temperature”.

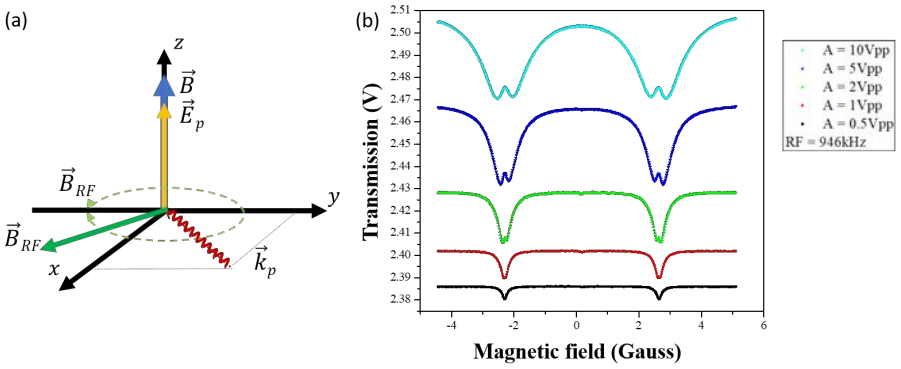

Figure 1: (a) Excitation geometry (b) The dependence of transmission signal on magnetic field with different RF amplitude values and laser frequency fixed to the $F_g = 4 \rightarrow F_e = 4$ hyperfine transition of ^{133}Cs D_1.

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Exciting Ytterbium Rydberg Atoms by the Evanescent Field of a Nano-Fiber

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Strongly inteacting Rydberg atoms form a growing platform for quantum optics and have been used to realize single photon sources, subtractors, switches, and gates. These applications rely on strong Rydberg-Rydberg interactions and collective excitations of many atoms which collectively enhance the coupling between few photons and the atoms.

One such system for manipulation of single photons is the Rydberg superatom: An ensemble of atoms smaller than the Rydberg blockade volume such that the entire ensemble can only contain a single excitation. The coupling to the mode of the driving field is collectively enhanced, and spontaneous emission back into this specific mode is enhanced. The Rydberg superatom therefore resembles a two-level atom coupled to a single field mode, and a cascaded system can be realized by creating many superatoms in a chain and probing them with the same probe beam.

To realize controlled Rydberg superatoms, it is neccessary that the cloud size of atoms and the waist of the Rydberg excitation beam are smaller than the Rydberg blockade radius. That property limits how many super atoms can be placed along the axis of the tightly focussed Rydberg excitation beam to guarantee a homogeneous excitation strength of the Rydberg light.

I will present how we plan to overcome this scalability limit by combining Rydberg superatoms with an optical nanofiber with a waist diameter much smaller than the wavelength, allowing super-extended evanescent fields. We use Ytterbium-174 which besides simple laser cooling has the advantage of having almost identical wavelenghts for the two-photon Rydberg excitation (399 nm and 395 nm) allowing the design of nanofibers guiding both fields.

This furthermore limits decoherence effects due to residual atomic motion. We plan to trap ytterbium superatoms in steerable optical dipole traps close to the surface of the optical nanofiber where Rydberg transisitions will be driven by the evanescent field of the fiber-coupled probe and Rydberg excitation light.

We aim to used this cascaded quantum system to create many-body systems where coupling between independent emitters are mediated by propagating photons. I will present the experimental progress towards these goals.

Confinement induced resonances in alkali – alkaline earth atom mixtures

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The production of alkali – alkaline earth atom dimers by magneto-association is rendered difficult because of the narrowness of Feshbach resonances due to the non-magnetic ground state of alkaline earth atoms. Here we present our approach for the formation of weakly-bound molecules of alkali – alkaline earth atoms which utilizes confinement induced resonances (CIR) in strongly interacting lower dimensional systems.

The eigenenergy spectrum of interacting harmonically trapped ^{87}Rb and ^{87}Sr atoms reveals the presence of confinement induced resonances (CIR), arising from the mismatch between the trapping frequencies of the two species. We calculate the position of confinement induced resonances in 1D and 2D and analyze the strength of the coupling. Furthermore, we theoretically investigate the efficiency of coherent molecule creation on different CIR's.

Observation of a microwave Feshbach resonance in sodium

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Controlling the interactions in a quantum gas is a fascinating feature that allows to explore phase diagrams of quantum systems. Tuning the interactions requires in general the use of a magnetic Feshbach resonance, which requires to confine the atoms in an optical trap in order to control independently the magnetic field and hence the interactions. Feshbach resonances also exist in the optical or in the microwave range, where an oscillating field is required to dress a molecular state near a molecular resonance. In this work, we investigate a microwave Feshbach resonance predicted for alkali [1], in a degenerate Bose gas of magnetically trapped sodium atoms.

A molecular resonance was predicted at a frequency near 1.6 GHz, corresponding to a molecular bound state situated approximately 200 MHz below the hyperfine atomic transition in the ground state of sodium. Previous studies in the optical domain located the molecular resonance at 1568 ± 10 MHz [2]. We excite a sodium quantum gas magnetically trapped under an atom chip with the high power microwave field produced by a microwave guide on the same chip. The large microwave amplitude (several gauss) allows us to locate the resonance easily around 1562 MHz, with a much better precision, of the order of 10 kHz. We also find a very broad resonance around 1280 MHz, which allows us to identify all relevant molecular transitions corresponding to different internal molecular spin states and model the molecular spectrum accurately. We record the two-body and three-body loss rates near the resonance, and discuss experimental protocols to evidence an effect of the microwave field on the atomic interactions.

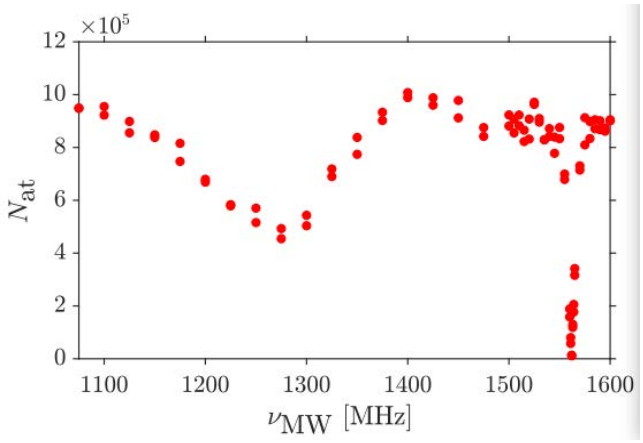

Figure 1: Molecular spectroscopy in the range 1.1–1.6 GHz, evidencing the narrow transitions around 1562 MHz as well as a broad molecular transition around 1280 MHz.

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Towards the nano-g with a cold atom absolute gravimeter

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Atom interferometry is a technology able to beat conventional devices in the domain of inertial sensors. With a sequence of light pulses, it is possible to realize an interferometer sensitive to inertial forces such as gravity in a gravimeter or rotation in a gyroscope. Since 2003, we have developed at SYRTE a colds atoms gravimeter (CAG) state-of-the-art today. It uses free-falling ^{87}Rb atoms, which experience a Mach-Zehnder sequence of two-photon Raman pulses driven by counter-propagating vertical lasers. We report a measurement of the Earth gravity acceleration with a stability better than conventional absolute gravimeters (5.7×10^{-8} m.s^{-2} in 1 s of measurement, down to 5×10^{-10} m.s^{-2} after 10 000 s) and with equivalent accuracy (2×10^{-8} m.s^{-2}).

The uncertainty budget is dominated by systematics related to wave-front aberrations as well as the initial position fluctuations of the atomic source. Because of the ballistic expansion of the cloud during the free fall, each atom experience different phase profiles at each transition, inducing in the measurement a phase shift difficult to estimate.

I will present our strategy to improve the accuracy of the measurement, based on a new optical trap setup for evaporating cooling and a new retro reflective mirror with better optical quality at the level of 1/100 λ peak to valley. With those improvements, we expect to improve the accuracy better than 1×10^{-8} m.s^{-2}.

Furthermore, we report a study of the loss of the interferometer contrast related to the length of the mirror pulse of the interferometer. Those losses fit well with a model of light shift inhomogeneity induced by fluctuation of the space profile of the Raman beam. This study gives specification on the quality of the beam required to optimize the contrast.

Relativistic calculations of electron–parent ion entanglement using the KRAKEN protocol

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Synopsis In systems with multiple open ionisation channels, such as in the case of fine-structure splitting of the valence shell, entanglement between an ejected electron and its Parent Ion (PI) may lead to a mixed state. Such states can not be fully characterised as wave-functions, but instead need to be described using density-matrix formalism. With recent developments in attosecond science, pump-probe methods such as KRAKEN have been developed to fully reconstruct the one-photon density matrix. This is done by interferometric measurements of the two-photon electron distribution. The present communication uses the Relativistic Random Phase Approximation with Exchange (RRPAE) method to directly calculate the one-photon density operator and its reconstruction.

In most atomic systems, single ionisation-channel continua are the exception, rather than the norm. When multiple ionisation channels are open, the purity γ of the state density operator can provide information on the electron–Parent Ion (PI) entanglement. This information may not be extracted using only an XUV pump, but can be obtained with the addition of a probe pulse. This is the principle behind pump-probe methods, which allow extracting time-dependent information by varying the pump-probe delay.

One recently developed interferometric pump-probe method aimed at reconstructing the one-photon density operator $\hat{\rho}_{\mathrm{XUV}}$ is known as KvanttillståndstomogRafi av AttoseKundsElektroNvågpaket (KRAKEN) [1]. KRAKEN combines an XUV pump with a two-colour IR probe, allowing for interference measurements of the population at any two intermediate energies ε_1 and ε_2. The retrieved information is assumed to be representative for the one-photon wave packet, allowing the density matrix elements $\langle\varepsilon_1|\hat{\rho}_{\mathrm{XUV}}|\varepsilon_2\rangle$ to be reconstructed.

From the point of view of theory, both the one- and two-photon matrix elements can be directly obtained, without the need for any of the assumptions relied on in the KRAKEN protocol. Thus, both $\hat{\rho}_{\mathrm{XUV}}$ and its KRAKEN reconstruction may be calculated—and compared—directly. The present work makes use of Relativistic Random Phase-Approximation with Exchange (RRPAE) [2] to simulate KRAKEN in argon, where the fine-structure splitting of the ground state results in separate ionisation channels. Both the $\hat{\rho}_{\mathrm{XUV}}$ and its KRAKEN reconstruction are calculated and compared to evaluate the assumptions present in the method.

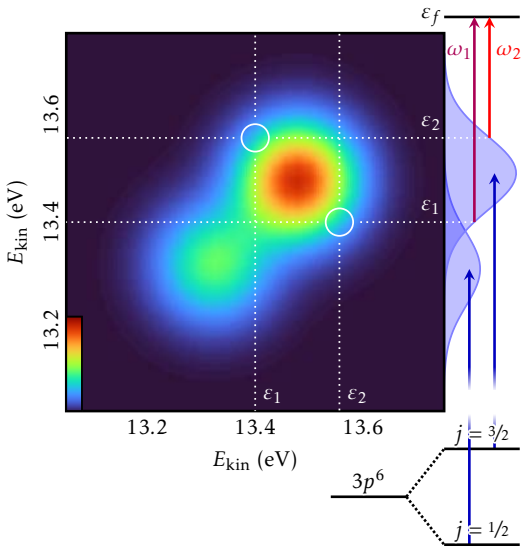

Figure 1. The magnitude of the calculated argon one-photon density operator $\hat{\rho}_{\mathrm{XUV}}$. Two maxima are present, due to fine-structure splitting of the $3p^6$ ground state. The matrix elements $\langle\varepsilon_1|\hat{\rho}_{\mathrm{XUV}}|\varepsilon_2\rangle$ can be reconstructed from the beatings induced at a final energy ε_f by a two-colour IR-probe. The two-photon ionisation paths are shown to the right.

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Ionization coss-section measurements in the quadrupole ion trap

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Cross-section data precisely describe various collision processes, especially collisions involving electrons as a projectile. While the measurements performed on neutral atoms are rather typical, conducting experiments on ions is an experimental challenge. Our recent work [1] showed that using an ion trap solves this problem.

In the case of electron-atom/ion collisions, cross-section data are typically described as a function of electron energy. Therefore, the accuracy of the measurements is directly related to the control of the monochromatic energy of the electrons used. Unfortunately, the RF electric field used in quadrupole ion traps affects both the trajectories and energies of the electrons. Thus, the electron energy spread affects the accuracy of the obtained data. We present a new experimental system with the electron gun integrated with the ion trap. In the applied geometry, the electron beam is emitted along the axis of the trap, which reduces the energy spread of electrons and thus increases the accuracy of measurements.

Figure 1: The vacuum chamber containing an ion trap with an integrated monochromatic electron gun.

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Optical tweezer optimisation for trapped-ion quantum simulator

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Trapped ions offer a natural platform for quantum simulation. They provide advantageous conditions such as long coherence times (h̃ours) and natural organization into lattice crystalline structures due to their interconnected interactions [1, 2]. With this setup one can perform quantum simulations by engineering spin-Hamiltonians whose interactions are mediated by the crystal's phonon modes [3, 4, 5, 6]. Our system is innovative as it adds optical tweezers, i.e. very tightly-focused light, which is used to manipulate the ion crystals' sound-wave spectra. This allows extra tunability over the ion interactions, paving the way to the simulation of a wide range of spin-Hamiltonians [7, 8, 9]. We show experimental progress on a trapped-ion tweezer setup, detailing a tweezer optimization routine and alignment on the ions. We characterize the beam profile and observe coherent population trapping of the ion states [10].

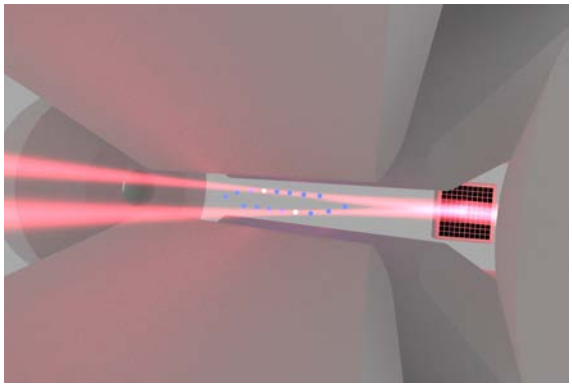

Figure 1: Optical tweezers produced via spatial light modulator adress ions in ion crystal.

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Theoretical study of Th III energy levels and transitions

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Multiconfigurational Dirac-Hartree-Fock [1] and relativistic configuration interaction [2] methods, which are implemented in the general-purpose relativistic atomic structure package GRASP2018, were used to calculate the energy levels of the $5f6d$, $6d^2$, $7s^2$, $5f^2$, $6d7s$ and $5f7s$ configurations for Th III. The accuracy of the energy levels is evaluated by comparison with experimental data [3] and with the theoretical method [4]. The accuracy of electric dipole transitions between states of these configurations is evaluated using the QQE method [5]. Extensive observations of a thorium-argon hollow cathode lamp emission spectrum were made, using a high-resolution Fourier transform spectrometer [3]. Energy levels, transition properties, and lifetimes were determined using the configuration-interaction plus all-order (CI+all) method [4]. Initial investigation of accuracy for energy levels is given in Table 1. Averaged relative differences with experimental data are given for our energy levels and for computed with CI+all method. A broader presentation of the study will be given at conference.

Table 1: Comparison of our computed energy levels (RCI) and CI+all [4] with the experiment [3].

Configuration	NL	$\overline{\Delta E/E}_{CI+all}$,%	$\overline{\Delta E/E}_{RCI}$,%
$5f7s$	4	3.3	5.2
$5f6d$	20	7.0	6.0
$6d^2$	9	13.8	5.3
$6d7s$	4	7.8	4.1
$7s^2$	1	3.9	9.0
$5f^2$	13	2.7	3.0
all	51	6.6	4.9

Acknowledgments: *This research paper has received funding from the Research Council of Lithuania (LMTLT), agreement No S-LJB-23-1 and JSPS Bilateral Joint Research Project (JPJSBP120234201).*

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The Fermionic Tonks-Girardeau gas: composite boson formation and a novel formulation of the ground state wave function

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Attractive p-wave one-dimensional fermions are studied in the fermionic Tonks-Girardeau regime in which the diagonal properties are shared with those of an ideal Bose gas. We study the off-diagonal properties and present analytical expressions for the eigenvalues of the one-body density matrix. One striking aspect is the universality of the occupation numbers which are independent of the external potential [1]. We show that the occupation of natural orbitals occurs in pairs, indicating the formation of composite bosons, each consisting of two attractive fermions. The formation of composite bosons sheds light on the pairing mechanism of the system orbitals, yielding a total density equal to that of a Bose-Einstein condensate. Additionally, we propose an alternative form of the Fermionic Tonks-Girardeau ground state. This poster is based on our recently accepted work in Physical Review Letters [2].

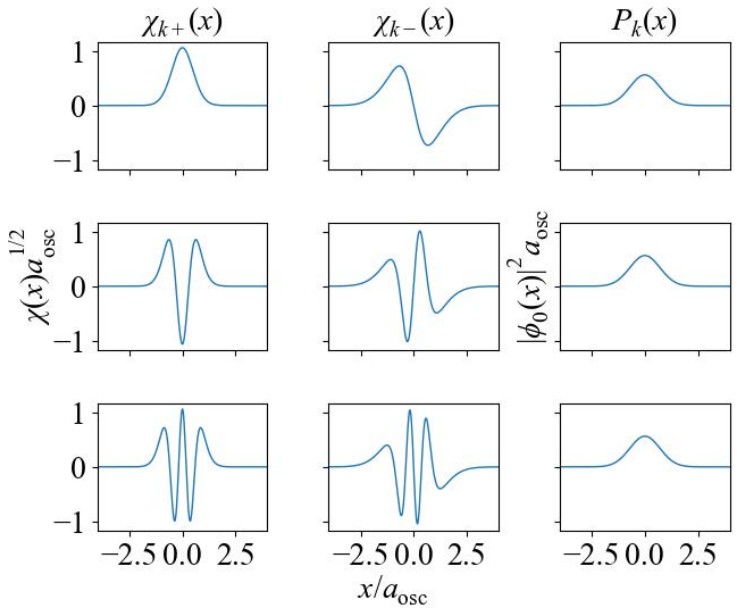

Figure 1: Fermionic natural orbitals and composite boson density profile in a harmonic trap potential for an even number of particles. First and second columns, the first six natural orbitals, $\chi_{k+}(x)$ and $\chi k(x)$, respectively, corresponding to the three largest doubly degenerate eigenvalues k =1,2,3 of the one body density matrix. Third column, the first three composite boson density profiles $P_k(x)$.

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Effects of curved geometry and finite temperature in dipolar Bose Einstein Condensates

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Dipolar Bose gases showcase a wide variety of physical phenomena, remarkably the formation of supersolids and ultra cold, self-bound droplets. This phenomenology stems from the unique combination of traits (long range character and anisotropy) of the dipole-dipole interaction (DDI). Because of its anisotropy, it is interesting to study the interplay of the DDI and a geometrically non-trivial confinement, like the shell-shaped traps that can be engineered under microgravity conditions in the NASA Cold Atom Laboratory. We explore the ground state configurations of a dipolar BEC immersed in a bubble trap, and show how the frustration induced by the confinement yields ring-shape arrangements of dipolar solids and supersolids.

In much the same way, the combination of anisotropy and long range character makes dipolar systems specially susceptible to the effect of thermal fluctuations, even at temperatures considerably lower than the BEC critical temperature, as recently demonstrated by experimental and theoretical works [1, 2]. We explore the thermal effects induced on a dipolar BEC confined in a tubular geometry, and show that temperature can alter the order of the superfluid-to-supersolid phase transition present at zero temperature [3].

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Tailoring population transfer between two hyperfine ground states of ^{87}Rb

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We investigate the coherent control over a complex multi-level atomic system using the stimulated Raman adiabatic passage (STIRAP). With rubidium-87 atoms, excited with circularly-polarized light at the D_1 line, we demonstrate the ability to decompose the system into three- and four-level subsystems independently interacting with light beams [1]. Focusing on the four-level system, we demonstrate that the presence of an additional excited state significantly affects the dynamics of the system evolution. Specifically, it is shown that, through the appropriate tuning of the light beams, some of the transfer channels can be blocked, which leads to better control over the system, allowing for the transfer of a several sublevels simultaneously rather than a single one. We also demonstrate that this effect is most significant in media free from inhomogeneous broadening (e.g., Doppler effect) and deteriorates if such broadening is present. For instance, the motion of atoms affects both the efficiency and selectivity of the transfer.

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Measuring black body radiation shifts with a dual species optical clock

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Optical clocks based on trapped ions can feature fractional uncertainties at the 10^{-18} level and below. For many such systems operated at room temperature, the largest frequency shift is caused by the AC Stark effect of thermal radiation. To correct this shift with small uncertainty, knowledge of the effective temperature T of black body radiation (BBR) perturbing the ion and the sensitivity $\Delta\alpha$ (differential polarizability) of the reference transition to BBR are necessary. The heating of the ion trap from radiofrequency (rf) losses causes an increase of T during operation. T can be estimated directly by operating the clock with different ion trap rf drive power and extrapolating to zero power. We demonstrate this approach using of the ${}^2S_{1/2} - {}^2D_{5/2}$ clock transition of ${}^{88}\mathrm{Sr}^+$ that features a well-characterized $\Delta\alpha$ [1]. Using an optical clock based on the ${}^2S_{1/2} - {}^2F_{7/2}$ transition of ${}^{171}\mathrm{Yb}^+$ as the reference, we find the frequency ratio of both clocks with 2.3×10^{-17} uncertainty [2]. This ratio and a measurement of the ${}^{171}\mathrm{Yb}^+$ clock frequency [3] yield the clock frequency value for ${}^{88}\mathrm{Sr}^+$. This result provides important information regarding a discrepancy found between previous measurements and supports a future reevaluation of the recommended standard frequency for ${}^{88}\mathrm{Sr}^+$ with reduced uncertainty. We further exploit the small uncertainty of $\Delta\alpha$ for ${}^{88}\mathrm{Sr}^+$ by calibrating the intensity of an infrared laser at the position of the trapped ion via the induced frequency shift. Measuring the frequency shift due to this calibrated intensity allows for the determination of $\Delta\alpha$ for other clock ions. In this way, we improve knowledge of $\Delta\alpha$ for the ${}^{171}\mathrm{Yb}^+$ ${}^2S_{1/2} - {}^2D_{3/2}$ and ${}^2S_{1/2} - {}^2F_{7/2}$ clock transitions by more than order of magnitude, enabling 10^{-18} and 10^{-19} uncertainty, respectively.

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Topological photon pumping in quantum optical systems

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We introduce the concept of topologically protected photon pumping in one-dimensional emitter chains with long-range interactions. Our theoretical investigation shows that the concept of topologically protected pumping survives even when sublattice symmetry is broken by all-to-all interactions. As a concrete technological example, we investigated three different popular quantum optics platforms, namely Rydberg atoms, dense atomic ensembles, and emitters coupled to waveguides with experimentally relevant parameters. We observe that despite the long-ranged character of the dipole-dipole interactions, dispersionless topological pumping allows to transport an excitation with a per cycle fidelity exceeding **99.9%**. Surprisingly, our study indicates that the long-ranged character of the dipole-dipole interactions enhances the robustness of the photon pumping process.

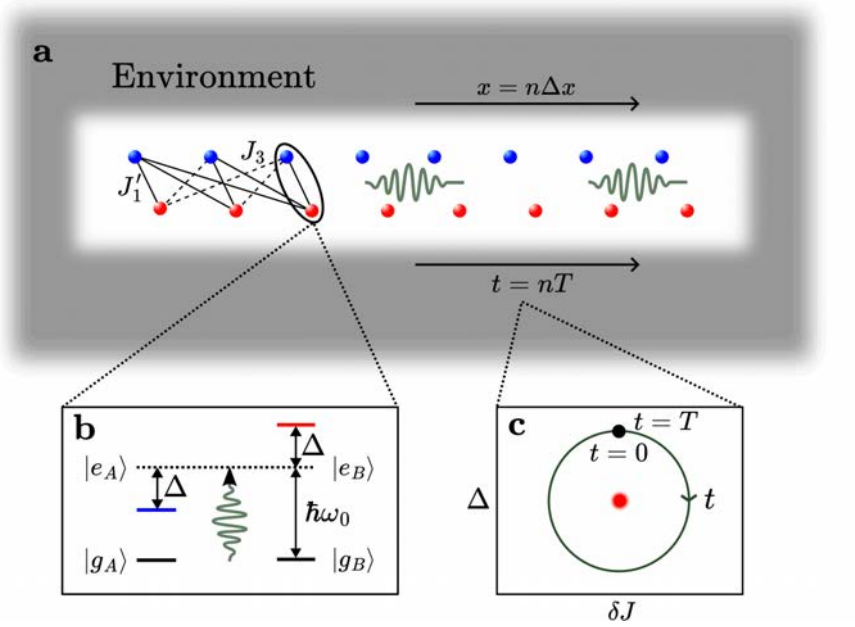

Figure 1: *Topological photon pumping on a quantum optical system.* **a:** All systems we consider can be generally described as a one-dimensional chain of emitters coupled to a common (Markovian) environment. The chain is formed by $N/2$ unit cells with two sublattices, A and B (blue and red, respectively). **b:** The emitters are considered to be identical two-level systems with ground (g) and excited (e) states separated by an energy $\hbar\omega_0$. **c:** By varying time-dependently the parameters of the system (here generically called Δ and δJ) in a periodic manner, a single photon is initially stored in the chain and transported (topologically pumped) across the lattice minimizing its dispersion.

Confinement induced resonances in alkali-alkaline earth atoms

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Ultra-cold mixtures have the potential to be excellent systems for exploring a variety of phenomena such as phase separation, pair superfluidity, polaron formation, and fermion-mediated interactions. However, it is challenging to test theoretical predictions for strongly interacting mixtures due to the three-body losses in these systems. In an experiment, we demonstrate that a mixture of ultracold 87Rb and 87Sr gases that interact resonantly exhibits a significant reduction in both heating and decay when confined to the quasi-2D regime by an optical lattice potential. The stabilization of the mixture leads to lifetimes of several hundred milliseconds without observable heating and is attributed to a strong suppression of the detrimental effects of three-body collisions. The observed stabilization should also apply to other resonantly interacting mixtures, providing an excellent starting point for creating ultracold ground-state molecules and exploring novel regimes in strongly interacting ultracold mixtures.

Cold Rydberg atoms for Strontium Optical Clock thermometry

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Optical clocks operate by locking an ultra-stable laser on a narrow atomic transition in the optical spectrum, realizing a stable and accurate frequency reference. By controlling environmental parameters and evaluating various systematic effects, the Strontium optical clock at SYRTE Laboratory currently achieves a relative frequency systematic uncertainty of approximately 1.7×10-17. At this precision, the energy shift of the clock's transition levels by the Black-Body Radiation (BBR) is a significant contribution to the clock inaccuracy, despite it being currently evaluated by calibrated thermal sensors placed around the clock vacuum system.

We propose a method for an in-situ, independent evaluation of the BBR frequency shift by exciting the clock atoms into a Rydberg state, therefore significantly increasing their BBR sensitivity [1]. The BBR will induce transitions to nearby Rydberg states [2], as well as photoionize the atoms, and we aim to experimentally detect this population redistribution over time. By developing a theoretical model of this state redistribution as a function of BBR spectra, a comparison to our measurements would provide a precise estimation of the radiation seen by the atoms.

To ensure a stable excitation to the Rydberg states for our detection, we are currently working on locking the Rydberg excitation laser. We propose here a method based on Electromagnetically Induced Transparency (EIT) signal.

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Dissipation in Superfluid Fermi Gases

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We study the dynamics and dissipation of a superfluid Fermi gas by means of the local density functional theory [1]. In particular, we study the collisions and reconnections of vortex lines, dissipation in fermionic Josephson junctions and the decay of the superfluid flow in a ring geometry. In the case of reconnecting vortex lines, the energy emitted in the process of reconnection is transferred between different length scales and subsequently dissipates. The reconnection dynamics is governed by a universal scaling law across the entire BCS-BEC crossover, where the distance between the lines scales as a square root of time to the reconnection [2, 3]. For the atomic Josephson junction, we show a clear difference in the mechanism of dissipation between the weakly and strongly interacting regimes. The dissipation in the strongly interacting regime occurs through a phase-slippage process, while in the limit of weak interactions, the main dissipation channel is the process of breaking Cooper pairs [4]. The dissipation mechanism is also studied in persistent currents in a ring geometry with a localized defect, where we study the time evolution of the superfluid flow. The nature of the flow dissipation depends on the interaction strength; in the BCS limit the pair-breaking mechanism occurs in the bulk superfluid in contrast to the strongly interacting regime, where the pair-breaking process is located in the vortex cores [5].

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Monochromatic electrons source for surface electronic microscopy

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By combining a monochromatic electrons source with high performance detectors, we build with the laboratories ISMO and SPEC a unique electronic microscope call HREELM. This microscope is able to make spatial imagery and analyse the surface vibrations interactions simultaneously. Applications include nanophysics, nanochemistry and photonics.

One of the most important thing for HREELM is the electron source. The flux must be higher than 100 pA and the energy dispersion must be lower than 10 meV to be able to resolve phonons, plasmons, etc... The spatial resolution is close to 10 nm [1]. To satisfy these criteria, we choose the Rydberg atom ionization. We use a cesium jet and three lasers to excite the atoms into a Rydberg state. Centrally drilled electrodes are used to impose an electric field on the Rydberg atoms[2].

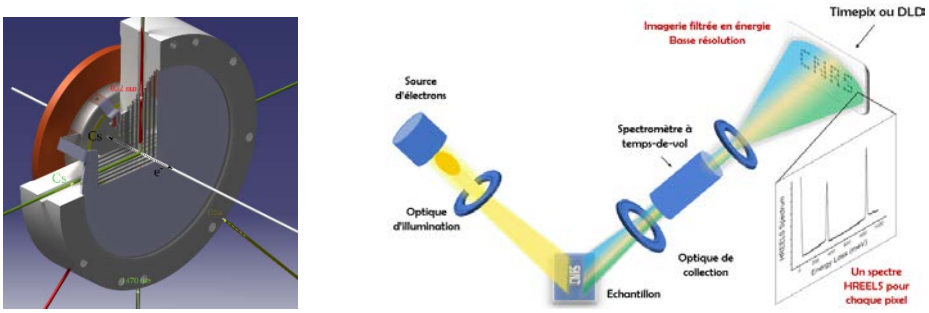

Figure 1: a) Schematic view of the electron source, b) Schematic of HREELM operation, with electron pulses arriving at the sample and then detected by the Timepix

Another important aspect of HREELM is the electron detection system. Indeed, after the interaction with the sample, the energy difference between two electrons will be very weak. Therefore, we need a detection system capable of resolving this small energy difference. To measure the energy difference between the electrons, we employ a time-of-flight measurement. The detection system consists of two microchannels plates coupled to a sensor that determines the position of the electrons and their arrival time on the sensor. As we use the time-of-flight measurement we need to know the time of arrival and the time of departure of the electrons. For this reasons we pulse the electron source[2]. There are several methods for pulsing the electron source, one of which involves pulsing the electric field to which the Rydberg atoms are exposed at a given wavelength. In our case, we would need pulses of the order of 100 ps[3].
I will present the latest status of the experiment during this meeting.

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A full-stack Quantum Computing Platform based on Trapped Neutral Rydberg Atoms

Yuri van der Werf, Deon Janse van Rensburg, Rianne Lous, Edgar Vredenbregt, and Servaas Kokkelmans on behalf of the Neutral Atom KAT-1 collaboration***

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The Neutral Atom KAT-1 collaboration is realising an implementation of a full-stack hybrid quantum computer. At its core is a quantum processor with qubits based on neutral atoms confined in optical tweezers. These qubits can be entangled through long-range interactions enabled by exciting the atoms to high-lying Rydberg states. Currently two such setups are in development in Eindhoven, one based on ^{88}Sr and the other based on ^{85}Rb atoms.

Here, we report on the latest progress of the rubidium based setup, where the qubit states are encoded in the hyperfine splitting of the Rb ground state. Using microwave excitation we drive Rabi oscillations between the qubit states and by applying a Stark-shifting laser beam it is possible to manipulate the phase evolution of the individual atoms and prepare arbitrary superpositions of the qubit states on each atom separately.

For the next step, two-photon excitation will be used to couple the qubit $|1\rangle$ state to a highly excited Rybderg level, thereby enabling the interaction between the qubits and allowing entangling operations. With these tools, a proof-of-principle implementation of this hybrid quantum computer can be offered as an online platform for external users. A major advantage of this tweezer-based platform is that scaling the number of qubits by an order of magnitude should be a relatively straight-forward excercise, by progressing to ever larger tweezer arrays, as recently shown by several other groups [**?**, **?**].

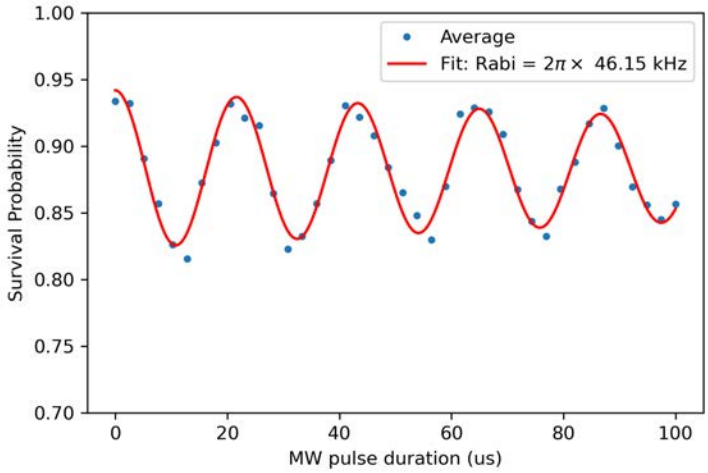

Figure 1: Microwave-driven Rabi oscillations of the hyperfine qubit states in trapped individual ^{85}Rb atoms

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Stark deceleration of molecules for precision measurements

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Precise measurements on molecules represent a highly sensitive approach to detect physics beyond the Standard Model. In the NL-eEDM collaboration, barium monofluoride (BaF) molecules are used to probe the electron electric dipole moment (eEDM) with high precision. The molecules need to be measured for as long as feasible to improve statistical sensitivity. This is accomplished by utilizing a traveling-wave Stark decelerator that reduces the longitudinal velocity of a beam of BaF molecules. Here we present the development of the high-voltage electronics required for the operation of the decelerator. The high-voltage waveforms are produced by means of home-made transformers. These need to have sufficient power output to overcome the capacitive load of the decelerator and to reach the desired voltage amplitude. Furthermore, a large enough bandwidth is required such that they can operate within the desired velocity range of the molecules. Precise control of the high-voltage waveforms is crucial for effective deceleration and the minimization of molecular losses. However, the complex equivalent circuitry of the decelerator makes this a challenging endeavor.

Exploring the "electronic memory" of vibrational dynamics in a laser-driven molecule: how electronic coherence and electronic-nuclear entanglement are shaping the non-Markovian electronic evolution

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Electronic coherences and electronic-nuclear entanglement are essential quantum correlations in a molecular system; they play a key role in many chemical and biological processes, and their functions are currently investigated in new domains like attochemistry or quantum biology. Non-Markovian quantum dynamics typically occurs when an open system is coupled to a structured or finite environment, or due to strong system-environment interactions. Quantum non-Markovianity is recognized as a resource capable to protect the evolution of an open quantum system from decoherence and dissipation, leading to revivals of its characteristic quantum properties, such as quantum coherence and entanglement. Our aim is to explore these quantum properties in the case of a diatomic molecule, using quantum information concepts.

Here we consider a diatomic molecule described in a bipartite Hilbert space $\mathcal{H}=\mathcal{H}_{el}\bigotimes\mathcal{H}_{vib}$ (a tensor product of the electronic and nuclear Hilbert spaces, neglecting rotation), and driven by laser pulses. The electronic subsystem can be analyzed as a driven open quantum system in the vibrational environment. In previous works [1, 2], we have shown that the evolution of the electronic subsystem in a molecule has an inherent non-Markovian character, correlated to the evolution of the electronic coherence and with the electronic-vibrational entanglement dynamics [3]. We will explore further this essential non-Markovianity of the electronic evolution, analyzing the molecular dynamics induced by chirped laser pulses which couple the electronic states $a^3\Sigma_u^+(6s,6s)$ and $0_g^-(6s,6p_{3/2})$ of the Cs_2 molecule [4, 5]. We shall use specific preparations implying the control of the vibrational tunneling in the $0_g^-(6s,6p_{3/2})$ double well potential, in order to observe the interplay between tunneling, the control of the vibrational environment, the evolutions of the electronic coherence and entanglement, and their effects on the resulting non-Markovian electronic dynamics.

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Accurate Tensor Network Simulation of realistic NV centers in diamond

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Diamonds have become one of the most popular solid-state platforms for quantum sensing, due to their capability of hosting optically active defects, e.g., nitrogen-vacancy (NV) centers [1]. The presence of ^{13}C atoms in the vicinity of the NV center is one of the dominant sources of decoherence that limits its use as a quantum sensor, especially in case of strong coupling. Even so, having such impurities opens up the possibility of designing nuclear spin-based quantum simulation platforms [2]. Being able to accurately simulate the action of such external degrees of freedom on the NV behavior gives us the opportunity to characterize and control them through different dynamical nuclear polarization protocols. In this work, we present accurate and efficient simulations, utilizing Tensor Network techniques, of a large number of nuclear spins coupled to the spin defect, following a star geometry. We consider the so-called nuclear spin orientation via electron spin locking (NOVEL) [3] polarization protocol and investigate the underlying quantum effects in both strong and weak coupling regimes as well as the limits of achievable polarization transfer in either case.

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Quantum trajectory nonlinear averages to distinguish different unravelings in resonance fluorescence

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The notion of quantum jumps was first introduced by Bohr in 1913 to describe the abrupt change of state of the electrons in atoms. It has been experimentally observed for the first time in trapped ions in 1986 using the concept of electron shelving, followed by many other quantum systems. The theoretical description of these investigations stimulated the development of quantum trajectory theory. The dynamics of quantities linear in the density matrix is governed by the usual Gorini-Kossakowski-Sudarshan-Lindblad master equation and is independent of the photodetection scheme. At the level of single realizations, different types of jumps can occur depending on the type of measurement. The dynamics of single trajectories influenced by the environment can be *unraveled* by a set of quantum stochastic equations.

The two most popular unravelings can be studied for resonance fluorescence with a single atom: the Poisson-type, corresponding to direct detection of the photons scattered from the two-level emitter, and the Wiener-type, revealing complementary attributes of the scattered field such as the wave amplitude and the spectrum. In [1], we propose a way to operationally distinguish these two unravelings appealing to stochastic conditional dynamics via quantum trajectories. The idea relies on performing a nonlinear operation on single-trajectory quantum mechanical averages and subsequently averaging over all different realizations comprising the ensemble. The asymptotic results extracted for weak and strong coherent driving of the atom are in very good agreement with the Monte-Carlo simulations. Our proposal, inspired by the single-atom apparatus of [2], is tested against commonly met experimental limitations, and can be readily extended to account for open quantum systems with several degrees of freedom.

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Discrete diffraction and beam propagation in an optically induced lattice in rubidium vapor

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We present an experimental study of the propagation of light through an optically induced lattice in a far-detuned Λ system in Doppler-broadened ^{87}Rb atomic vapor. Discrete diffraction patterns are observed when a probe beam propagates through an optically induced lattice created by the interference of two coupling laser fields intersecting at a small angle. Of particular interest are the cases where the probe beam is focused into one lattice site, with distinctly different results for focusing into the maximum and minimum of the interference pattern.

We investigate the influence of various experimental parameters, such as probe beam size, probe and coupling laser detunings and intensities, and the concentration of atoms on the observed diffraction patterns and the patterns' contrasts. The study of such periodic structures in atomic systems with tunable optical properties, analogous to weakly coupled waveguides, provides valuable input for future experimental implementations of this system to study complex quantum and optical physics phenomena, such as the study of non-Hermitian physics, PT-symmetric potentials [1], and photonic Floquet topological insulators [2].

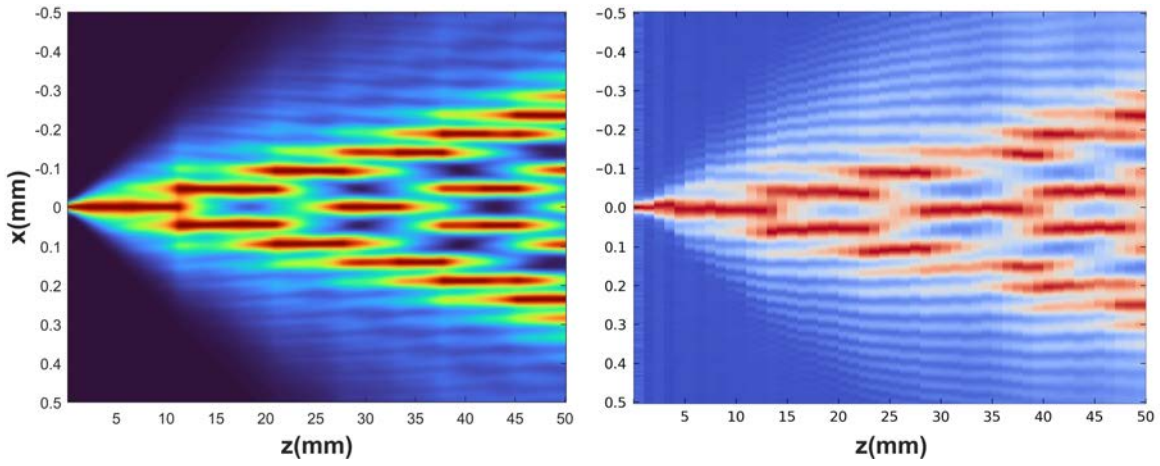

Figure 1: Simulated (left) and measured (right) propagation of light through an optically induced lattice in rubidium vapor.

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USOC: Ultra-precise, shock-resistant optical clocks

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Optical atomic clocks require atoms to be cooled down to ultracold temperatures. In optical lattice clocks, this imposes long dead times between clock interrogations, leading to the Dick effect - aliasing of high-frequency local oscillator noise into low-frequency clock noise. This can be circumvented by using a continuous scheme, in which atoms are cooled and loaded into a moving optical lattice which conveys them between spatially separated interrogation regions [1]. Dick noise is the the most significant source of noise in current neutral atom optical clocks, and eliminating it would potentially allow these clocks to reach the quantum projection noise limit [2].

This talk will introduce a new strontium-based continuous optical lattice clock, loaded from a MOT operating on the mid-infrared $2.92\,\mu\mathrm{m}$ $5s5p^3P_2$ to $5s4d^3D_3$ transition. Operating the MOT on these metastable states has several advantages over the typical $689\,\mathrm{nm}$ MOT used for Sr; most significantly, it can operate close to the interrogation region without significantly perturbing the $698\,\mathrm{nm}$ $5s2^1S_0$ to $5s5p^3P_0$ clock transition. Additionally, the $689\,\mathrm{nm}$ MOT requires additional lasers for population recycling, and has a higher recoil limit ($250\,\mathrm{nK}$ vs $12\,\mathrm{nK}$) [3, 4]. Simultaneous with the high-precision clock interrogation, the clock laser will be stabilised via high-bandwidth interrogation of the atoms, granting less stringent requirements for laser pre-stability. This removes the need for a large stabilisation cavity, opening the door to portability and reducing the susceptibility of the system to mechanical shock.

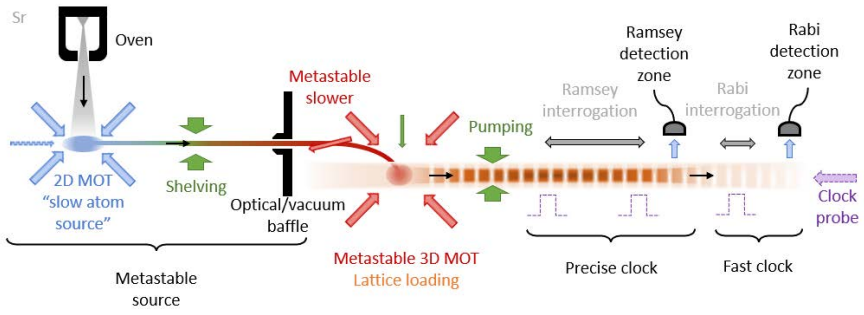

Figure 1: Continuous lattice clock schematic.

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Sympathetic cooling in ultracold Rb-Hg system

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Multi-species atomic clocks attract significant interest due to the potential for improving their accuracy and stability using multiple elements. The frequency stability of multi-species optical clocks may be enhanced through simultaneous measurements performed on multi-species ensembles of many atomic absorbers. Improving frequency accuracy could involve leveraging atoms with two reference transitions exhibiting different sensitivities to external fields. An example here could be a mercury atom [1]. Utilizing of multi-component systems as the basis for atomic clocks requires precise measurements of their mutual interaction. One of the significant consequences of the mutual interaction between components is sympathetic cooling, which can lower the temperature of one of the components, thereby permitting longer coherent laser-atom interaction times and, consequently, shorter averaging times.

In this study, we conducted measurements to evaluate the sympathetic cooling effect in a two-species system within a double Rb-Hg magneto-optical trap setup [2]. Since the Doppler cooling limit for mercury (30.5 μK) is lower than that for rubidium (145 μK), we measured the temperature of rubidium to assess the performance of sympathetic cooling. The temperature of the Rb cloud was determined both in the presence of a cooled Hg atomic cloud and in its absence, and the results were then compared. While the absence of structure splitting in the ground state of Hg bosons prevents the application of sub-Doppler cooling methods, the ^{87}Rb isotope used in the experiment can be sub-Doppler cooled below the Doppler limit.

To determine the temperature of the cooled Rb atomic cloud, we employed a measurement method involving the observation of the cloud's size during its ballistic expansion in free fall after turning off the trapping potential, including both magnetic field and cooling laser beams. Subsequently, we tracked the spatiotemporal evolution using a fluorescence imaging technique assisted by a probe laser beam. The temperature of the Rb cloud, obtained from fitting the data to the ballistic expansion equation, indicates a reduction from 149(6) µK to 87(2) µK. These findings demonstrate a significant sympathetic cooling effect in the Rb-Hg double MOT system.

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Microwave-free magnetometry with nitrogen-vacancy centers in nanodiamonds

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Recently, a novel effect has been observed in the fluorescence of nitrogen-vacancy (NV) color-center ensembles in diamond as a function of a static external magnetic field [1]. A subtle drop in the fluorescence level is observed around the zero magnetic field, termed zero-field resonance (ZFR). Its width ranges from $\sim$0.1 to $\sim$1 mT, with the fluorescence contrast reaching up to several percent, depending on the diamond properties. Interestingly, a similar effect is observable in an ensemble of nanodiamonds with arbitrary orientations [2].

In this study, we investigate the dependence of the ZFR width and contrast on the size of the diamond (ranging from 30 nm to 3000 nm) and the strength of a bias magnetic field applied transversely to the scanned field. Additionally, we conduct optically detected magnetic resonance (ODMR) measurements to quantify the net strain splitting of the zero-field ODMR resonance across various nanodiamond sizes. We then compare these findings with the width and contrast of the ZFR features for both nanodiamonds and bulk samples. Our observations provide compelling evidence of cross-relaxation effects in the NV system occurring close to zero magnetic fields [2]. Furthermore, we show the evolution of ZFR structures when the sample is cooled down to cryogenic temperatures.

Finally, we demonstrate the potential of this technique for practical, microwave-free magnetometry. Utilizing drop-casted NV nanodiamonds, we map magnetic fields above micrometer-sized current-carrying structures. Additionally, we conduct similar experiments in an endoscopic configuration using a high-numerical-aperture imaging fiber bundle. These findings pave the way for the development of NV-diamond borescopes and endoscopes.

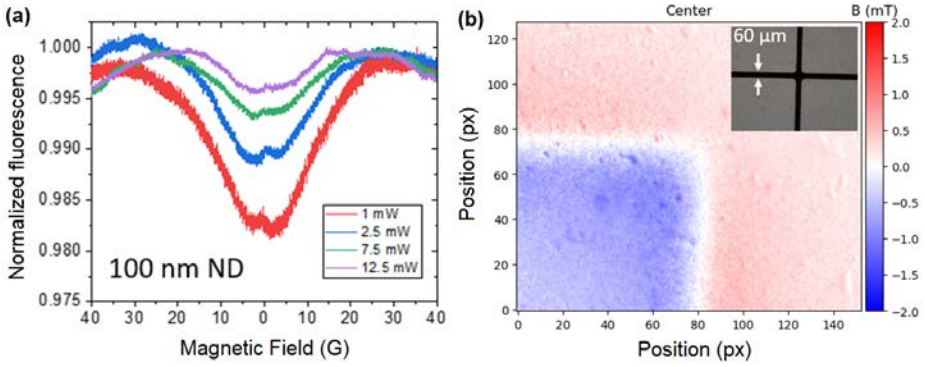

Figure 1: a) ZFR spectra as a function of ND size; b) magnetic field map above a cross-like structure with current flowing thorugh the bottom and left arms of the structure shown in the inset. Each line is 6o μm wide.

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Ultrahigh-density spin-polarized hydrogen isotopes from the photodissociation of hydrogen halides: new applications for laser-ion acceleration, magnetometry, and polarized nuclear fusion

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Recently, our group produced spin-polarized hydrogen (SPH) atoms at densities of at least 10^{19}cm^{-3} from the photodissociation of hydrogen halide molecules with circularly polarized UV light and measured them via magnetization-quantum beats with a pickup coil. These densities are approximately 7 orders of magnitude higher than those produced using conventional methods, opening up new fields of application, such as ultrafast magnetometry, the production of polarized MeV and GeV particle beams, such as electron beams with intensities approximately 10 times higher than current sources, the study of polarized nuclear fusion, for which the reaction cross sections of D–T and D–He reactions are expected to increase by 50% for fully polarized nuclear spins and the production of various nuclear-spin polarized molecules, through SPH reactions, on nanosecond timescales, for pump-probe NMR detection with signal enhancement.

For more information, see Ref. [1, 2, 3, 4, 5]

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Potential model, autocorrelation function and plasma spectroscopic diagnosis

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Plasma based technology is a field of growing interest is a wide range of fields such as medicine, agriculture, microelectronics, materials growing, surface processing or treatment of environmental pollution. A necessary previous step for any of these applications is a reliable characterization of plasma physical parameters: electron density and temperature and gas temperature. Spectroscopic diagnosis is one of the mostly employed techniques for this purpose because of its non invasive character. This methodology is based on the measure of the atomic and molecular emission profiles of the species present in the plasma. A key point is, therefore, the relationship between the line shape and the physical properties of the plasma surrounding the emitting atom that leads to a perturbation of the spectrum [1]. Here we will focus on the so called Stark broadening induced by the interaction with the charged species of the plasma. From an atomistic point of view, the line shape is a function of the autocorrelation function of the atomic dipole moment that depends on the local fluctuations of the electric field inside the plasma [2]. In this communication we present different models for an effective potential to study the Stark broadening of the Balmer emission line, reported in the literature for a wide range of plasma conditions [3].

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Ultrafast Rydberg experiments with ultracold atoms

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Rydberg atoms, with their giant electronic orbitals, exhibit dipole-dipole interaction reaching the GHz range at a distance of a micron, allowing ultrafast quantum operations. However, this has never been harnessed so far because of the stringent requirements on the fluctuation of the atom positions and the necessary excitation strength. Here, we introduce novel techniques to enter and explore this ultrafast Rydberg regime [1, 2].

I will introduce the *Rydberg timescale* to position the various limits and opportunities set by atomic physics properties of Rydberg orbits, as well as the technical challenges in reaching them with today's experimental tools. We will then look at how we excite Rydberg atoms as fast as physically possible ($\sim$ 10 picoseconds) by using techniques of pulsed lasers, non-linear optics and spectral optimization. With the atoms *instantaneously* transferred to the Rydberg states, we will discuss how fast they can interact with each other through long-range dipole-dipole interaction and I will show experiments displaying a coherent evolution in the nanosecond timescale. Finally, we will consider how the dipole-dipole interaction couples coherently the internal electronic Rydberg dynamics to the external motional degrees of freedom (position, momentum). I will show signatures of this effective "spin-motion" coupling with atoms trapped both in optical tweezers as well as in optical lattices. I will conclude with opportunities offered by quantum control of the motional states through motional squeezing or Floquet engineering, and the prospects for quantum simulation in this enlarged Hilbert space [3].

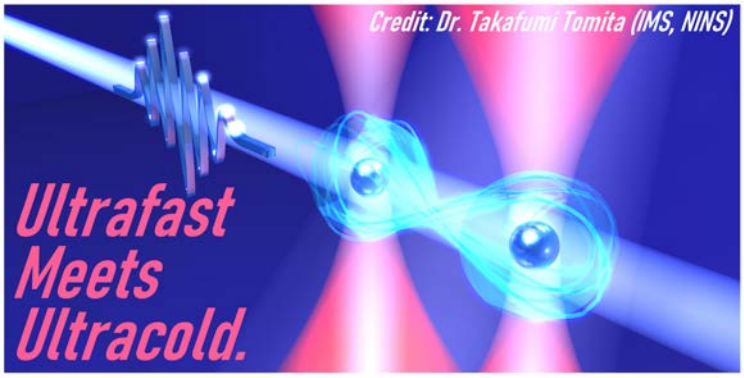

Figure 1: Artistic view of two trapped atoms in strong interaction after excitation by an ultrashort laser pulse.

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