



57th Conference of European Group on Atomic Systems

BOOK OF ABSTRACTS

21 – 25 June 2026, Toruń, Poland

Nicolaus Copernicus University in Torun

www.egas57.org

EGAS57 Toruń, Poland 21-25.06.2026

Organizers



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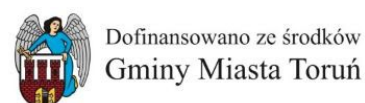
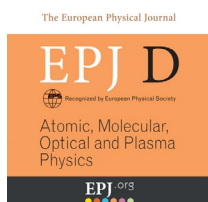


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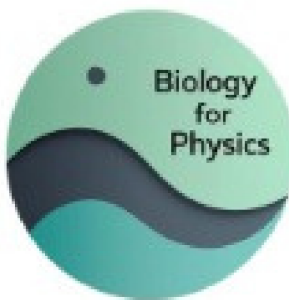
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EGAS Conference

About EGAS

EGAS stands for the European Group on Atomic Systems, formerly known as the European Group on Atomic Spectroscopy (name changed in 2004). The origins of EGAS date back to 1968 with the Caen Colloquium, known as EGAS 0. The first official meeting, EGAS I, was held in 1969 at the Laboratoire Aimé Cotton in Orsay. The first EGAS chair was A. Kastler, Nobel Prize laureate in Physics (1966). EGAS is a section of the Atomic, Molecular and Optical Physics Division (AMOPD) of the European Physical Society (EPS). It provides a forum for presenting advances in atomic, molecular and optical physics and fosters scientific collaboration across Europe.

Last five editions of EGAS conference

EGAS 56 (WITH ECAMP 15) 2025, Innsbruck, Austria

EGAS 55 2024, Granada, Spain

EGAS 54 2023, Strasbourg, France

EGAS 53 (WITH ECAMP 14) 2022, Vilnius, Lithuania

EGAS 52 2021, Virtual, Zagreb, Croatia

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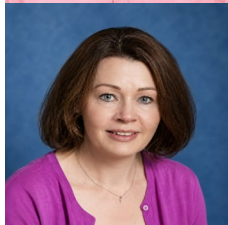
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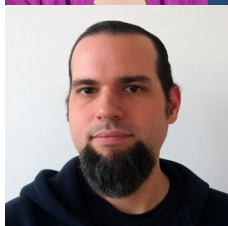
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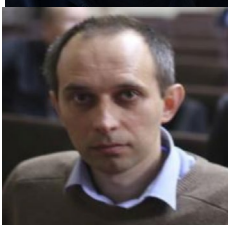
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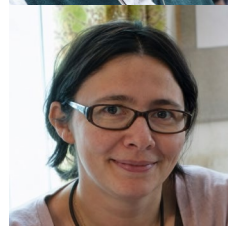
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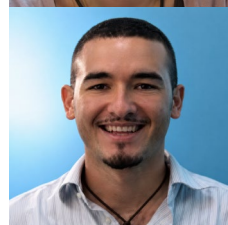
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Vrije Universiteit
Amsterdam



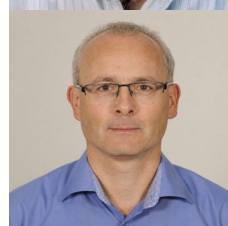
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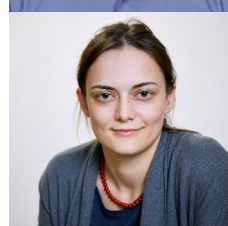
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EGAS57 Plenary Speakers



Prof. Klaus Blaum

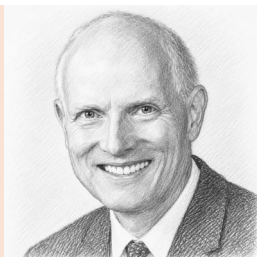
Max Planck Institute for Nuclear Physics
Heidelberg

Talk Title: Precision at the Extremes:
Exploring the Standard Model with
Trapped Exotic Ions

Prof. Ana Maria Rey

JILA, University of Colorado Boulder

Talk Title: New Frontiers in Quantum
Simulation and Sensing via Cavity-
Mediated Interactions



Prof. Paul S. Julienne

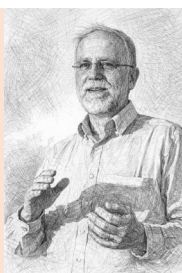
Joint Quantum Institute (JQI), University of
Maryland and NIST

Talk title: Making ultracold Li_2 molecular
isotopologues using Feshbach resonances
among different spin species of Li atoms

Prof. Mark Saffman

University of Wisconsin-Madison

Talk title: Quantum computing with
atomic qubit arrays



Prof. Alexander G. G. M. Tielens

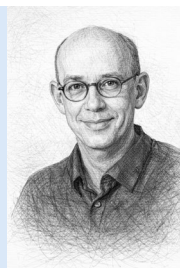
Leiden University

Talk Title: Aromatic Molecules in the
Molecular Universe

Prof. Ekkehard Peik

Physikalisch-Technische Bundesanstalt,
Braunschweig

Talk Title: Nuclear laser spectroscopy of
thorium-229



EGAS57 Invited Speakers

Kjeld Eikema

Precision determination of the alpha-helion charge radius difference with ultracold helium

Matteo Zaccanti

Anomalous diffusion and localization in a disorder-free atomic mixture

Janko Nauta

A new era of fundamental physics tests with antihydrogen

Maksim Kunitski

Small weakly-bound van der Waals clusters studied by Coulomb Explosion Imaging

Kiyotaka Aikawa

Quantum squeezing of the motion of a levitated nanoparticle

Alejandro González-Tudela

Programming quantum optical simulators

Barbara Maria Latacz

Coherent measurements of the (anti)proton magnetic moment at BASE-CERN

Vincent Loriot

Photoionization attosecond dynamics from molecules of increasing size

Åsa Larson

Theoretical investigation of charge recombination processes involving the BH reaction complex relevant for fusion plasmas

Michał Matuszewski

Quantum and classical computing with optical neural networks

James N. Bull

Radiative Cooling Dynamics Governing PAH Survival in Astrophysical Environments

Jan Marcus Dahlström

Time-Dependent Strong-Coupling Phenomena at XUV Wavelengths

Sonja Franke-Arnold

Atomic state interferometers for structured light

EGAS57 Invited Speakers cont'd

Francesco Pepe

Non-Markovian dynamics and bound state generation in waveguide QED

Andrzej Dragan

Relativistic reason for quantum probability amplitudes

Lucile Rutkowski

Optical frequency comb spectroscopy at low temperatures for laboratory astrophysics applications

Daniel Lisak

Metrology of gas temperature and amount of substance using high-resolution molecular spectroscopy

Antoine Camper

Laser cooling of positronium with broadband laser pulses: towards intense, cryogenic Ps clouds

EGAS57 Schedule

SUN 21/06	MON 22/06	TUE 23/06	WED 24/06	THU 25/06
08:30	registration	9:00 Julienne Saffman	9:00 Tielens	9:30 Franke-Arnold
9:15	opening	9:50 Saffman	9:50 Peik	10:00 Pepe
10:00	Blaum	10:40 coffee	10:40 general assembly	10:30 Dragan
10:50	Rey	11:10 Aikawa	10:50 coffee	11:00 coffee
11:40	coffee	11:40 Łukasiewicz	11:20 Gonzalez - Tudela	11:30 Rutkowski
12:10	Eikema	12:00 Haubenreißer	11:50 Brown	12:00 Lisak
12:40	Piwiński	12:20 Weber	12:10 Gładysz	12:30 Camper
13:00	Vukics	12:40 Latacz	12:30 lunch	13:00 closing+lunch
13:20	lunch	14:20 Hakalla	12:50 Loriot	
15:00	Nauta	14:50 Alighanbari	14:00 Giampaolo	
15:30	Das	15:10 coffee	14:50 Sierant	
15:50	Karam	15:30 Larson	15:30 coffee	15:30 excursions
16:10	Boronat	16:00 Steinel	16:00 Matuszewski	16:00 excursions
16:30	Minh Nhut Ngo	16:30 Kepa	16:00 Mika	16:30 excursions
	poster session + snacks	16:50 Wright	16:50 Wright	16:50 excursions
18:30		17:10 poster session + snacks	16:50 transportation to Golub castle & Gala Dinner	17:10 excursions
		19:00		19:00 Open Lecture Andrzej Dragan

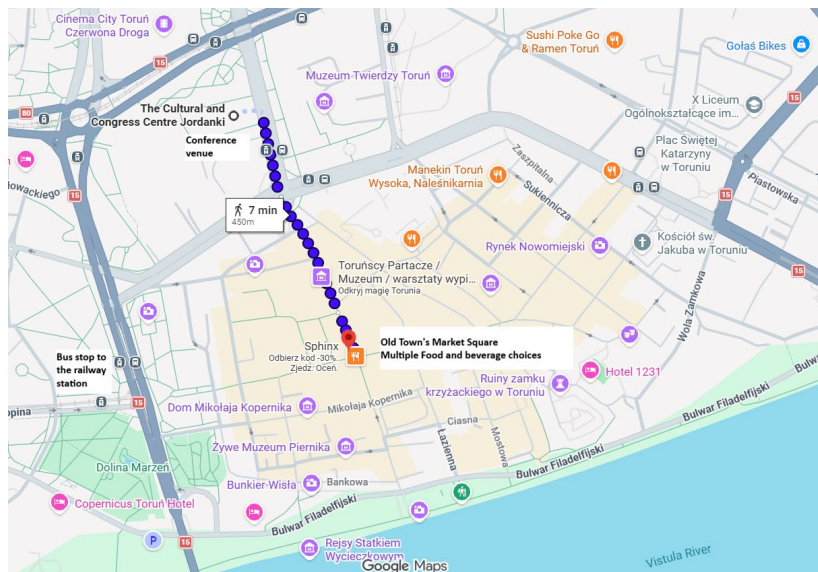
EGAS57 Practical Information

Conference Venue:

[CKK Jordanki, ul. Aleja Solidarności 1-3, Toruń](#)

[Artystyczna Bistro](#) at the venue offers lunch choices (limited seating)

Old Town and Restaurants/Pubs Area (7 min. walking distance)

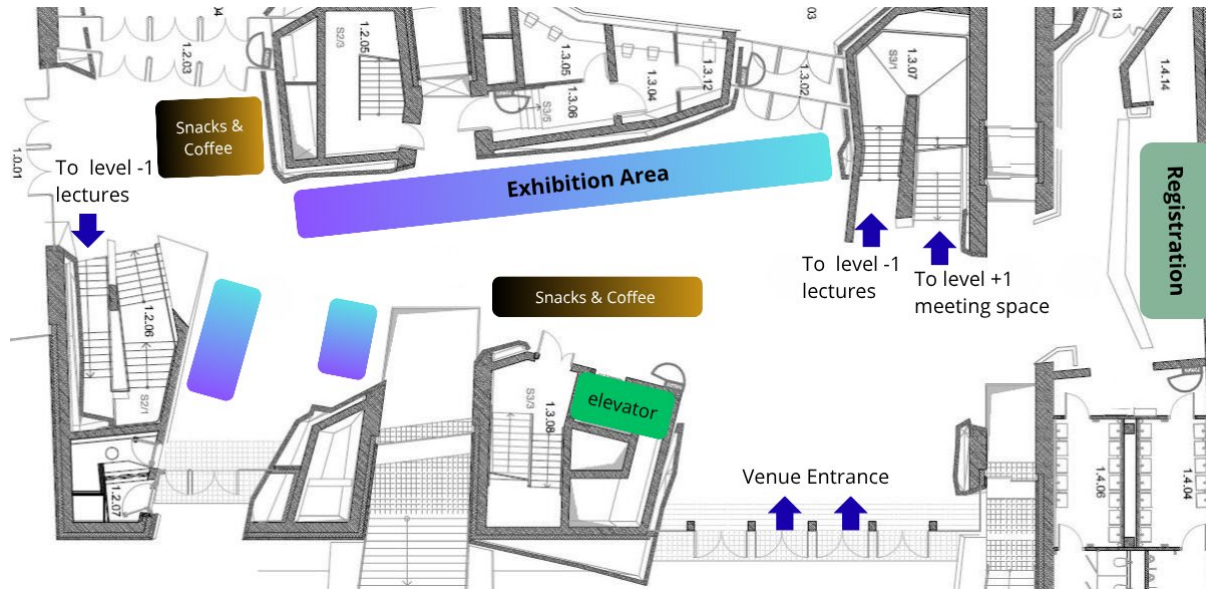


[Institute of Physics](#) - for laboratory visits (tours on Wednesday) and scientific discussions (7 min. walking distance)

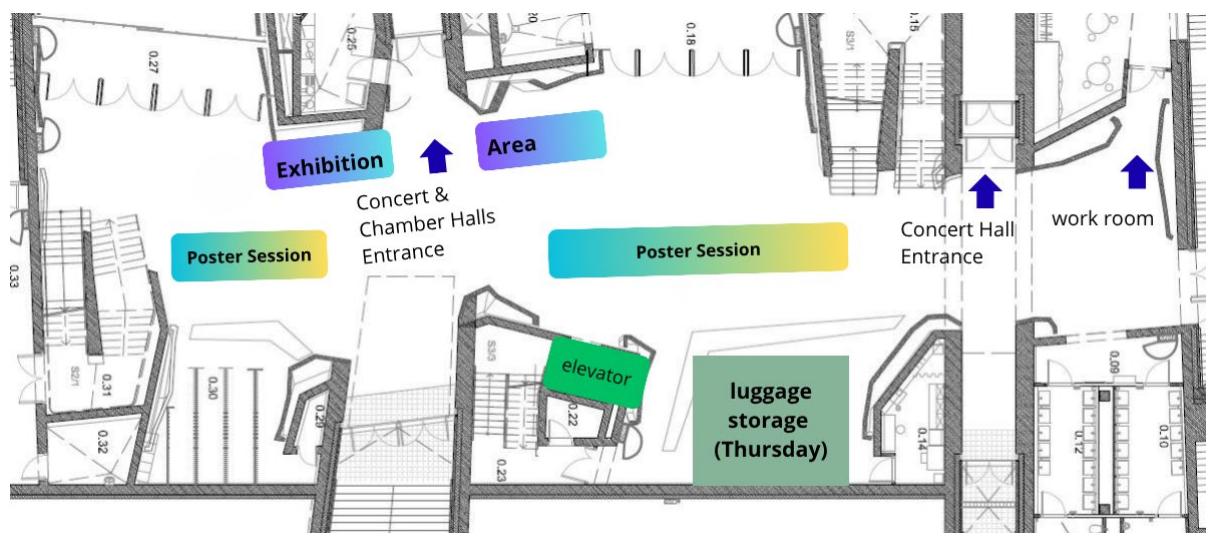


EGAS57 Venue maps

Level 0 - venue entrance, registration, coffee breaks and exhibition area



Level -1 - entrance to the lecture halls, poster sessions, working room and exhibition



meeting area and space to relax can be found on Level +1

EGAS57 Internet Access

All the participants can use WiFi network

SSID: EGAS57WiFi pass: AtomicSystems

Encryption: WPA

Scan the QR Code to log in faster

Computer with internet access is also available in the **work room** at level -1



EGAS57 Social Programme

WELCOME RECEPTION - Sunday June 21 at 7pm in [Collegium Maximum](#)
(address Plac Rapackiego 1)

CONFERENCE DINNER - Wednesday June 24th Golub-Dobrzyń near Toruń
Complementary buses to Golub Castle will leave at
4pm from the Conference Venue

EXCURSIONS:

Sunday, June 21st - guided walking tour of Toruń's breathtaking medieval Old Town, a UNESCO World Heritage site. Free of Charge, **start at 5 pm from** [Collegium Maximum](#) (address Plac Rapackiego 1)

Thursday, June 25th :

- Kayaking along the Drweca River, start 2:30 pm from the Venue, price 200 PLN per person
- Visit to the Astronomical Observatory in Piwnice , start 4:00 pm from the venue, price 100 PLN per person
- Fort IV Torchlight Tour, start 2:30 pm from the venue, price 100 PLN per person

More information about Thursday's excursions available at egas57.org .

All reservations for both the Sunday welcome tour and the Thursday afternoon excursions must be made online via the official booking platform: egas57.bookero.pl.

PLENARY SESSIONS

Monday Plenary Session – Concert Hall (09:00–10:40)

- **K. Blaum:** Precision at the Extremes: Exploring the Standard Model with Trapped Exotic Ions
- **A. M. Rey:** New Frontiers in Quantum Simulation and Sensing via Cavity-Mediated Interactions

Tuesday Plenary Session – Concert Hall (10:00–11:40)

- **P. S. Julienne:** Making ultracold Li₂ molecular isotopologues using Feshbach resonances among different spin species of Li atoms
- **M. Saffman:** Quantum computing with atomic qubit arrays

Wednesday Plenary Session – Concert Hall (9:00–10:40)

- **A. Tielens:** Aromatic Species in the Molecular Universe
- **E. Peik:** Progress in nuclear laser spectroscopy of thorium-229

CONFERENCE LECTURES

Monday Session One – Concert Hall (12:10–13:20)

- **K. Eikema:** Precision determination of the alpha-helion charge radius difference with ultracold helium
- **M. Piwiński:** Anion source for antiprotonic atom formation
- **A. Vukics:** Photon-blockade breakdown as a first-order dissipative phase transition in zero dimension

Monday Session Two – Chamber Hall (12:10–13:20)

- **M. Zaccanti:** Anomalous diffusion and localization in a disorder-free atomic mixture
- **A. Gavalda:** Directional observation of the superradiant emission of an ensemble of atoms
- **S. Kuhr:** Many-body quantum phases in programmable light potentials

Monday Session Three – Concert Hall (15:00–16:30)

- **J. Nauta:** A new era of fundamental physics tests with antihydrogen
- **A. Das:** Quantum Interference in Identical Particle Collisions
- **C. Karam:** Probing weakly bound levels of a Dysprosium atom pair
- **J. Boronat:** Order by heating a quantum gas: an unexpected effect

Monday Session Four – Chamber Hall (15:00–16:30)

- **M. Kunitski:** Small weakly-bound van der Waals clusters studied by Coulomb Explosion Imaging
- **D. Charczun:** Cavity-enhanced frequency comb spectroscopy of complex molecules in the long-wave mid infrared
- **A. Bonnin:** Metrology of Electromagnetic Fields Using Cold Rydberg Atoms
- **M. N. Ngo:** Ultra-High-Resolution Mid-Infrared Spectroscopy using Sub-Hz Stabilized Quantum Cascade Lasers: towards Tests of Fundamental Physics

Tuesday Session One – Concert Hall (11:10–12:40)

- **K. Aikawa:** Quantum squeezing of the motion of a levitated nanoparticle
- **G. Łukasiewicz:** Dynamics of coupled spin ensembles in a K-Rb-3He comagnetometer
- **D. M. Haubenreiser:** Chiral Recognition with High-Energy Photo- and Compton Electrons
- **A. Weber:** A universal approach to saddle-point methods in attosecond science

Tuesday Session Two – Chamber Hall (11:10–12:40)

- **A. González-Tudela:** Programming quantum optical simulators
- **P. Grochowski:** Optimal control of mechanical systems in the quantum regime
- **L. L. Brown:** Microwave dressed Rydberg atoms coupled through a single-photon transition to a superconducting coplanar waveguide resonator
- **P. Gładysz:** Light interactions with polar quantum systems

Tuesday Session Three – Concert Hall (14:20–15:30)

- **B. M. Latacz:** Coherent measurements of the (anti)proton magnetic moment at BASE-CERN

- **R. Hakalla:** VUV-UV-VIS FT spectroscopy and the first observation of interference between indirect interaction pathways in CO
- **S. Alinghabari:** New experimental approaches to high-precision studies of molecular hydrogen ions

Tuesday Session Four – Chamber Hall (14:20–15:30)

- **V. Lorient:** Photoionization attosecond dynamics from molecules of increasing size
- **S. M. Giampaolo:** Experimental Generation of Many-Body W States via Topological Frustration in Rydberg Quantum Simulators
- **A. Sierant:** Quantum noise scaling in continuously operating multiparameter sensors

Tuesday Session Five – Concert Hall (16:00–17:10)

- **J. Å. Larson:** Theoretical investigation of charge recombination processes involving the BH reaction complex relevant for fusion plasmas
- **M. Steinell:** Polarizability measurements employing Yb⁺ and Sr⁺ optical clocks for systematic uncertainties below 10⁻¹⁸
- **H. T. Kepa:** Rydberg thermometry in a Strontium Optical Lattice Clock

Tuesday Session Six – Chamber Hall (16:00–17:10)

- **M. Matuszewski:** Quantum and classical computing with optical neural networks
- **J. Mika:** Coherent dynamics in an ensemble of warm atoms at optical frequencies
- **S. Wright:** Aluminum monofluoride: three MOTs, and a laser-coolable molecule that can bounce off surfaces

Wednesday Session One – Concert Hall (11:20–12:50)

- **J. N. Bull:** Radiative Cooling Dynamics Governing PAH Survival in Astrophysical Environments
- **C. Baynham:** Differential, single-photon interferometry with the strontium-87 clock transition for AION
- **J. Snikeris:** Metastable level lifetime measurements and experimental transition rates in Fe II and Ti II for nebular diagnostics
- **J. de Montbel:** A new X-ray spectroscopy technique to probe the metastable fraction in an ECR ion source plasma

Wednesday Session Two – Chamber Hall (11:20–12:50)

- **J. M. Dahlström:** Time-Dependent Strong-Coupling Phenomena at XUV Wavelengths
- **B. E. Ramírez Galindo:** Matter-wave interferometry of metal nanoparticles as a platform for fundamental and metrological insight
- **P. Justus:** High-Precision Spectroscopy of Single Molecular Hydrogen Ions at ALPHATRAP
- **M. Słowiński:** Cavity-enhanced spectroscopy in the deep cryogenic regime for quantum sensing and metrology

Thursday Session One – Concert Hall (09:30–11:00)

- **S. Franke-Arnold:** Atomic state interferometers for structured light
- **F. Pepe:** Non-Markovian dynamics and bound state generation in waveguide QED
- **A. Dragan:** Relativistic reason for quantum probability amplitudes

Thursday Session Two – Concert Hall (11:30–13:00)

- **L. Rutkowski:** Optical frequency comb spectroscopy at low temperatures for laboratory astrophysics applications
- **D. Lisak:** Metrology of gas temperature and amount of substance using high-resolution molecular spectroscopy
- **R. Caravita:** Laser cooling of positronium with broadband laser pulses: towards intense, cryogenic Ps clouds

MONDAY POSTER SESSION

(16:30 – 18:30)

- P01 – **H. Fosnes**: Towards a tabletop storage ring for visualizing charged-particle motion
- P02 – **M. Jungers**: Series of doubly excited states converging to the double-ionization threshold of Strontium atoms
- P03 – **T. Kilich**: Magnetic shielding in the atomic hydrogen anion
- P04 – **M. Klempka**: Zeeman hyperfine structure of atomic lutetium by laser spectroscopy investigations
- P05 – **M. Lepers**: Analysis of the luminescence properties of $\text{Pr}^{3+}:\text{YAG}$ within the framework of an extended Judd-Ofelt theory
- P06 – **M. Umiński**: Decaying Feshbach resonances in ultracold $\text{Er} + \text{Li}$ and $\text{Dy} + \text{K}$
- P07 – **S. Mieloch**: Feasibility studies of laser cooling in the cobalt atom
- P08 – **A. Arnold**: Single-beam grating-chip 3D and 1D optical lattices
- P09 – **A. Arnold**: Practical primary thermometry via Doppler broadening
- P10 – **R. Bala**: Isotopic mass effects on collisional parameters in a dual-species atomic clock
- P11 – **R. Bala**: Computational study for the bound states of $^{171}\text{Yb}-^{174}\text{Yb}$ molecular system
- P12 – **A. Bouillon**: Proposal for Production of Ca Heavy-Rydberg States by Electron Transfer From Ultra-Long-Range Rydberg Molecules
- P13 – **O. S. Burrow**: Overcoming capture limitations in grating magneto-optical traps with a 2D MOT
- P14 – **B. Bégoc**: Magnetic trapping and non-destructive microwave detection of cold atoms on an atom chip
- P15 – **A. Das**: Observation of Scattering Resonances in Ion-Neutral Collisions
- P16 – **C. Blondel**: Diffusion of atoms produced by photodissociation in an I_2 vapour: pressure dependence of surface recombination and a correction of the decay time of the fundamental mode
- P17 – **D. Lee**: Improving an ^{87}Sr Clock Atom Interferometer with Squeezed States
- P18 – **I. MacCuish**: Progress towards an experimental platform for investigating superfluid & vortex dynamics within binary BECs
- P19 – **E. R. J. Alhadi**: High-Resolution REMPI Spectroscopy for Molecular Characterization
- P20 – **D. Aumiler**: Nonlinear refractive index in warm rubidium vapor
- P21 – **T. Badr**: Excitation of a degenerate Rb gas in a shell trap
- P22 – **S. Bilicki**: Hollow-Core Fibre Platform for Sr Optical Clocks
- P23 – **M. Bober**: Towards active superradiance clock with cold strontium atoms
- P24 – **R. Chell**: Analysis and Mitigation of Bandwidth Nonlinearity in CRDS for HighAccuracy Optical Gas Metrology
- P25 – **R. Chell**: Heterodyne Cavity Ring-Down Spectroscopy for Accurate HD Line-Shape Analysis
- P26 – **S. Davidson**: Ground-state cooling of mixed-ion crystals in the intermediate Lamb-Dicke regime

- P27 – **P. Eberschweiler**: AQuRA, a prototype industrial transportable optical clock
- P28 – **L. Gianfrani**: Isotope shift spectroscopy in mercury vapours for new physics search
- P29 – **L. Gianfrani**: Precision spectroscopy of ethylene at 6.79 μm : absolute frequency calibration for muonic hydrogen spectroscopy in the FAMU experiment.
- P30 – **T. Groh**: Probing Nuclear Interactions Through Isotope Shift Spectroscopy of Mercury
- P31 – **J. Grondin**: High-Resolution Spectroscopy of Ca Rydberg Stark States and Determination of the Ca^+ Dipole and Quadrupole Polarizabilities
- P32 – **R. Hakalla**: Further observations of the comet-tail system in $^{12}\text{C}^{17}\text{O}^+$
- P33 – **N. S. Iturrioz**: Dual Laser Locking for Ytterbium via Modulation Transfer Spectroscopy
- P34 – **K. Jachymek**: High - resolution FT-UV study of the $\text{B}^2\Sigma^+ - \text{X}^2\Sigma^+$ system of $^{12}\text{C}^{17}\text{O}^+$: $\text{B}^2\Sigma^+, v = 0, 1$ levels revisited
- P35 – **L. Kau**: Towards quantum logic spectroscopy of highly charged heavy ions for novel optical clocks
- P36 – **D. Kierski**: Cryogenic spectrometer- benefits and perspectives for further technical development
- P37 – **M. Collignon**: Barium fluoride deceleration using temporary ionization
- P38 – **F. Mattiotti**: Fast and slow scrambling in many-body long-range interacting systems
- P39 – **M. Gancewski**: Rigorous quantum scattering calculations for fundamental and atmospheric studies
- P40 – **P. Gakkhar**: Fock-space relativistic coupled-cluster calculations of the properties of Th^{3+} nuclear clock
- P41 – **S. Heider**: Optical Dipole Trapping of Laser Cooled Mercury Atoms for Precision Physics
- P42 – **P. Holzenkamp**: CPT Test in the Lepton Sector – The LSym Experiment
- P43 – **D. Y. Knapp**: Towards State Preparation and Precision Spectroscopy of Weakly-Bound H_2^+
- P44 – **I. Kortunov**: High-accuracy optical spectroscopy of a single molecular ion in a Penning trap
- P45 – **B. E. Asenbeck**: Towards a scalable ion trap architecture - Trapping 2D ion arrays in a surface penning trap
- P46 – **N. Diepeveen**: Optical tweezers for trapped ion quantum simulations
- P47 – **A. Dąbrowska**: Optimization of two-photon absorption in three-level atom. The role of correlations, indistinguishability, and atomic parameters
- P48 – **S. Ganguly**: Integrated Photonic Devices for Hybrid Cavity QED with Rydberg Atoms and Superconducting Circuits
- P49 – **E. Garnaoui**: Benchmarking a machine-learning differential equation on a neutral-atom logical processor
- P50 – **E. Garnaoui**: Towards Fault-Tolerant Quantum Computing using Neutral Atoms
- P51 – **B. Gerritsen**: Mediating entangling gates between polar molecules using microwave dressed Rydberg atoms
- P52 – **Y. Pathak**: Four-Wave Mixing in Warm Vapor for Nonclassical State Engineering via the Coherent Superposition of Photon Addition and Subtraction

- P53 – **F. S. P. Ojeda**: Digital-twin of a neutral-atom quantum processor for fault-tolerant quantum computing
- P54 – **P. Głowacki**: Physical Layer Precursors of the Quantum Internet of Things (Q-IoT)
- P55 – **V. B. Kumar**: UMK26-A new exchange tuned exchange-correlation functional for DFT with superior performance
- P56 – **A. Hul**: Two microwave-shielded ultracold molecules in an optical tweezer
- P57 – **S. Izadshenas**: Single Molecule Detection in hBN Metasurfaces
- P58 – **K. Jachymski**: Spin-boson models with competing interactions
- P59 – **A. K. Jha**: Neutral Atom Tweezer Array Quantum Computing at NQCC
- P60 – **N. Klimkin**: Spontaneous symmetry breaking in nonlinear superradiance
- P61 – **M. Valipour**: Optimization of two-photon absorption: Unidirectional photon pairs
- P62 – **G. Singh**: Sensitivity of neutron capture reaction rates to precise nuclear inputs
- P63 – **L. Pruvost**: Nonlinear mixing of optical vortices to entangle photonic orbital angular moments

TUESDAY POSTER SESSION

(17:10 – 19:00)

- P01 – **H. Schmidt**: Storage-ring experiments with polycyclic aromatic hydrocarbon ions
- P02 – **J. Okoński**: Neutral, cationic, and anionic alkali-metal and alkaline-earth-metal monohydrides: Interaction potentials, dipole moments, and rovibrational structure
- P03 – **L. Palanky**: Laser slowing and cooling of aluminium monofluoride
- P04 – **R. Poulou**: Measurement of the lifetime of the metastable 5d 2D_{3/2} level of Ba⁺
- P05 – **R. Poulou**: Initial-state control in mutual neutralization of Si⁻ with Na⁺ or K⁺ revealing strong violations of Wigner's spin-conservation rule
- P06 – **D. Cabello Soto**: High-resolution laser photodetachment spectroscopy of Na⁻
- P07 – **F. Vallée**: Caesium photoionization for monochromatic electrons source for surface electron microscopy
- P08 – **N. Vlekken**: Multi-laser stabilization system for ultracold-Rydberg-atom and precision-spectroscopy experiments
- P09 – **M. Naudson**: Collective early-time spontaneous decay of a strongly driven cold atomic cloud
- P10 – **A. Meyroneinc**: Dissipative spin manipulation in a SU(N) symmetric Fermi gas
- P11 – **Y. Li**: A new interconnection platform for neutral atom arrays.
- P12 – **I. Nandi**: Progress in Optical Dipole Trap Towards Photo-Association Spectroscopy
- P13 – **M. Pawlak**: Ultraprecise determination of quantum defects and ionization energy of the cesium atom
- P14 – **A. de Montbel**: When probing Balmer transitions reveals low-energy ion-atom collision dynamics
- P15 – **M. Shundalau**: Strongly dipolar alkali-metal-silver molecules: Electronic structure and spectroscopic properties
- P16 – **M. Suchorowski**: From Scale Invariance to Universal Droplets: Generalised GPE for Attractive 2D Bose Gases
- P17 – **A. Vukics**: Collective inhibition of light scattering from atoms into an optical cavity at a magic frequency
- P18 – **V. Zhelyazkova**: Towards studying ultracold ion-molecule reactions in supersonic beams
- P19 – **E. Kovlakov**: Precision laser spectroscopy of trapped ¹⁷³Yb⁺ ions using a bath of ultracold atoms
- P20 – **J. Lodewyck**: High accuracy calibrations of the International Atomic Time with a Sr optical lattice clock
- P21 – **J. Borkowski**: Modeling of superradiance in color centers in diamond in the theory of quantum open systems
- P22 – **P. Morzyński**: Transient sensitivity of optical atomic clocks and prospects for active-clock-based detection schemes

- P23 – **L. Möller**: Development of cw laser systems in the deep-UV and vacuum-UV ranges
- P24 – **P. Olejarczyk**: High-power optical cavity - towards optical trapping of molecular hydrogen
- P25 – **L. Pagot**: Evaluation of wavefront aberrations in cold-atom inertial sensors
- P26 – **M. Piwiński**: Development of a pulsed atomic anion source for antiprotonic atom formation
- P27 – **S. Ryzner**: The $^{13}\text{C}^{18}\text{O}$ $A1\Pi(v=2) \rightarrow a3\Pi(v=13)$ Indirect Perturbation: Detection, Mechanism, and Surprises
- P28 – **A. Sahu**: Dual wavelength high-finesse cavity for neutral mercury clock
- P29 – **A. Stasik**: VUV - FT Spectroscopy of the Cameron System ($a3\Pi - X1\Sigma^+$) and deperturbation analysis of the $a3\Pi(v=4)$ state of $^{12}\text{C}^{16}\text{O}$
- P30 – **M. Słowiński**: New beyond-Voigt line-shape profile recommended for the HITRAN database
- P31 – **P. Ticku**: A Three-Colour MOT for Sustained Superradiant Lasing
- P32 – **F. Waldherr**: Zinc as a platform for precision metrology
- P33 – **S. Wójciewicz**: High-resolution spectroscopy of the oxygen B band for atmospheric applications and HITRAN2024
- P34 – **Y. Xu**: High-precision gas thermometry based on broadband optical frequency comb spectroscopy
- P35 – **Z. Zhang**: Robust population inversion by adiabatic passage in a continuous atomic beam for superradiant lasing
- P36 – **M. Malicka**: FT-spectroscopy of the $^{12}\text{C}^{18}\text{O}$ rare isotopologue and deperturbation analysis of the $A1\Pi(v=1-3)$ level
- P37 – **H. Medhat**: Predictive Gaussian Modeling of Spin Squeezing and Inter-Isotope Entanglement in a Dual-Isotope Mercury Comagnetometer
- P38 – **E. Mocchiutti**: The FAMU experiment at the RIKEN-RAL muon facility: precision measurement of the ground-state hyperfine splitting in muonic hydrogen
- P39 – **A. Ouf**: The ground state hyperfine splitting in muonic hydrogen experiment (HyperMu) at PSI
- P40 – **B. Özdalğic**: Hyperfine Structure Analysis of Neutral Terbium (Tb I) using Fourier Transform Spectroscopy
- P41 – **J. Peszka**: Low energy positive muons microbeams for fundamental physics
- P42 – **J. Richter**: Prospects of probing atomic parity violation with structured light
- P43 – **D. Dąbrowski**: Excited electronic states of the helium dimer including relativistic, adiabatic and QED effects
- P44 – **H. Sewell**: Triatomic YbCaF molecules for measurement of the nuclear magnetic quadrupole moment of Ytterbium 173
- P45 – **I. Maiti**: Joint Optimization of Source and Detection System in Entanglement Based BB84 Protocol
- P46 – **E. Minarelli**: Optical Skyrmions irradiating an atomic medium
- P47 – **V. Mittal**: Discrete time quantum walk of locally interacting walkers
- P48 – **V. Novichenko**: Floquet treatment of polar quantum system ultrastrongly coupled with light
- P49 – **C. A. Robledo**: A Zeeman Slower of AIF molecules
- P50 – **A. Pal**: Selective Preparation of Collective States via SUPER Excitation: Toward Bio-inspired Energy Efficient Configuration

- P51 – **A. Ghosh**: Purcell enhancement by the edge states of zig-zag graphene nanoflakes
- P52 – **M. Pelc**: On the impact of plasmonic character of optical resonances on Purcell enhancement at the atomic scale
- P53 – **M. Szturo**: Absorption Spectrum of Bilayer Triangular Graphene Flakes
- P54 – **M. Kosik**: GRANAD: A software package for simulating 2D materials with adatoms under external illumination
- P55 – **H. Septi  n-Gonz  lez**: Towards a measurement of the electron’s electric dipole moment with trapped YbF molecules
- P56 – **S. Sharma**: Beyond single-atom coupling: Self-organization through cavity-induced atom-pair interactions in a Fermi gas
- P57 – **J. Sobkowski**: Thermal effects versus magnetic field effects in the study of nitrogen colour centres in diamond
- P58 – **Y. Percin**: Davies-Morris-Shore Framework for Multilevel Quantum Batteries: Dark and Funnel States in Interacting Qutrit Systems
- P59 – **M. Taouzinet**: Atom Transport Benchmark and Parallelization for Scalable Neutral-Atom Quantum Processing
- P60 – **G. P. Teja**: Cavity-QED tools for MBQC with optical binomial-codes
- P61 – **C. Rich**: Molecular-state readout via resonant blockade between individual polar molecules and Rydberg atoms
- P62 – **K. Wadenpuhl**: Switching Rydberg interactions by three orders of magnitude using a terahertz field
- P63 – **B. K. Mani**: Relativistic Fock-space coupled cluster calculations of highly charged ions for probing atomic clocks and fundamental symmetries of nature
- P64 – **P. J. Robert**: Heterodyne Atom Interferometry for Ultralight Axion Dark Matter Detection
- P65 – **M. Sugra**: Laser Spectroscopy measurements of ^{169}Tm in the atomic beam unit

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Plenary

Sessions

Precision at the Extremes: Exploring the Standard Model with Trapped Exotic Ions

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The four fundamental interactions and their symmetries, along with the fundamental constants and properties of elementary particles – such as masses and magnetic moments – form the foundational structure of the universe and underpin the well-tested Standard Model (SM) of particle physics. Conducting stringent tests of these interactions and symmetries under extreme conditions, at low energies and with the highest precision, for example by comparing particles and their counterparts, the antiparticles, allows us to probe for potential physics beyond the SM. Advancing these tests beyond their current limits requires the development of innovative experimental techniques.

This overview highlights recent technical advancements and measurements of atomic and nuclear masses, as well as g-factors, with unprecedented precision, performed on individual or a few cooled exotic ions stored in Penning traps. Notably, these experiments have among others enabled the most precise tests of bound-state quantum electrodynamics and have significantly improved the accuracy of several key fundamental constants.

New Frontiers in Quantum Simulation and Sensing via Cavity-Mediated Interactions

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Atoms and photons are the fundamental building blocks of our universe. Their interactions govern the physical world, yet become remarkably complex in many-body quantum systems. Understanding and controlling these interactions is a central challenge in modern quantum science.

In this talk, I will explore how ultracold atoms trapped in optical cavities provide a powerful platform for studying and engineering atom–light interactions. Photons confined in cavities can mediate long-range interactions across many internal atomic states, enhancing energy scales and enabling the observation of rich many-body phenomena. These systems offer new ways to simulate iconic models of real materials and to engineer novel Hamiltonians with multi-body interactions beyond those found in nature.

Finally, I will discuss how cavity-mediated interactions enable the generation of quantum entanglement and help overcome fundamental limits in state-of-the-art atomic clocks and interferometers, opening new possibilities for quantum sensing.

Making ultracold Li_2 molecular isotopologues using Feshbach resonances among different spin species of Li atoms

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This talk examines the prospects of making the ultracold molecules, $^6\text{Li}_2$, $^7\text{Li}_2$, or $^6\text{Li}-^7\text{Li}$, with different spin species of Li atoms via magnetoassociation followed by STIRAP. This theory work uses new fitting of spectroscopically derived potentials to characterize precisely the Feshbach resonance properties of ultracold $^6\text{Li} + ^6\text{Li}$, $^7\text{Li} + ^7\text{Li}$, and $^6\text{Li} + ^7\text{Li}$ collisions [1]. The large difference in Feshbach molecule spin properties among these cases are due to the different mass scaling of the last bound state below threshold of the three Li_2 isotopologues. Two-color STIRAP production of ultracold $^6\text{Li}-^7\text{Li}$ molecules should be possible in both the singlet and triplet manifolds of all three isotopologues, enabling the future study and control of the coherent quantum dynamics of such molecules.

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Quantum computing with atomic qubit arrays

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Large arrays of neutral atoms are a leading modality in the race towards useful quantum computation. Systems with more than 1000 qubits in 2D arrays and gate fidelities approaching three nines are being developed by many academic and industrial groups. I will present recent progress at University of Wisconsin-Madison and Infleqtion with physical and logical qubit encodings. Interesting challenges remain in scaling the size and performance to the levels needed for quantum utility. Ultimately a modular approach to quantum computation will enable scaling to millions of qubits, with inter-module connections enabled by photonic links. Recent results on entangling atoms with photons for scaling a modular architecture will be presented.

Aromatic Species in the Molecular Universe

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Over the last 20 years, we have discovered that we live in a molecular Universe: A Universe with a rich and varied organic inventory; A Universe where molecules are abundant and widespread; A Universe where molecules play a central role in key processes that dominate the structure and evolution of galaxies. A Universe where molecules provide convenient thermometers and barometers to probe local physical conditions. Understanding the origin and evolution of interstellar and circumstellar molecules is therefore key to understanding the Universe around us and our place in it and has therefore become a fundamental goal of modern astrophysics.

The field is heavily driven by new observational tools that have become available over the last 20 years; Ground-based and space-based observatories have opened up the IR and sub-millimeter window. In particular, spectroscopic observations with NASA's James Webb Space Telescope (JWST) reveal a diversity of aromatic species in the Universe and a rich chemistry driving molecular complexity.

Our progress in understanding the Molecular Universe is greatly aided by close collaborations between astronomers, molecular physicists, astrochemists, spectroscopists, and physical chemists who work together in loosely organized networks. In this talk, I will sketch the progress that we have made after the launch of JWST and outline some of the challenges that are facing us. The focus will be on understanding the role of aromatic species in the organic inventory of regions of star and planet formation that may well have contributed to the prebiotic roots to life.

Progress in nuclear laser spectroscopy of thorium-229

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The thorium-229 nucleus with its 8.4 eV isomer is a unique system for studies at the interface between nuclear and atomic physics, with an excitation energy in the range of transition energies of valence electrons, and therefore accessible for the methods of precision laser spectroscopy. After the first resonant laser excitation of the nuclear transition in 2023/24 that solved the needle-in-the-haystack problem of searching for the accurate transition wavelength, there is strongly increased activity in this topic. Among possible applications, the development of a nuclear clock seems particularly attractive. This clock would offer high accuracy, high stability, and high sensitivity in clock-based tests of fundamental principles of physics, involving the strong interaction in addition to electromagnetism. There are two main approaches for realizing such a nuclear clock, using either laser Mössbauer spectroscopy of thorium-doped crystals, or laser-cooled thorium ions in radiofrequency ion traps.

Important progress has been made with narrow-linewidth laser sources for the required radiation at 148 nm. While four-wave-mixing of nanosecond pulses in xenon or high-harmonic generation of an infrared femtosecond laser have been applied in the first experiments, we have now demonstrated the first CW all-solid-state laser system at 148 nm using second harmonic generation in strontium tetraborate [1]. The laser is based on three sequential frequency doublings, starting from a diode laser at 1187 nm that is well suited for linewidth narrowing and for frequency comparisons with optical atomic clocks. Using this system in cooperation with the group of Th. Schumm at TU Wien, we show that the nuclear resonance can be probed with a power of less than 1 nW and that the resonance signal can be detected in absorption rather than in fluorescence [2]. This eliminates the slow nuclear fluorescence decay from the detection process and offers a considerable advantage for clock operation through fast signal acquisition. We use absorption spectroscopy for the quantitative characterization of two different Th-centers in calcium fluoride and measure the isomeric shift between them. One of the centers shows a very small static electric crystal field gradient $< 0.1 \text{ V/\AA}^2$, to be compared to gradients in the range of $100 \text{ V/\AA}^2$ observed earlier. This indicates a center with high symmetry of the ions surrounding the thorium nucleus, promising nuclear resonance lines that are less sensitive to the lattice spacing.

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Conference
Lectures

Precision determination of the alpha-helion charge radius difference with ultracold helium

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Precision spectroscopy measurements on calculable systems are widely used to perform tests of theory, but also for determinations of fundamental constants, nuclear charge radii, and as a probe of physics beyond the standard model. We will present spectroscopy in ultracold ^3He and ^4He , on the $2^3\text{S}_1 - 2^1\text{S}_0$ transition at 1557 nm.

Our latest measurements have been performed on a Bose-Einstein condensate of ^4He trapped in a magic-wavelength optical dipole trap, leading the highest spectroscopic accuracy until now for helium of 48 Hz. For this purpose, we developed methods to observe and subsequently suppress systematic Doppler shifts from the BEC oscillating in the optical trap, and we referenced the experiment via a White Rabbit link to a remote hydrogen maser at the Dutch Metrology Institute (VSL).

Combined with our previous measurement in ^3He [1] we determine an improved isotope shift, and using recent theory [2], we derive a charge radius squared difference between the alpha and helion particle with unprecedented accuracy [3]. Our new result is consistent with other recent determinations (see [1-5]) and confirms that the QED theory discrepancy seen in excited states of helium [5] is not apparent in the isotope shift.

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Anion source for antiprotonic atom formation

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The development of reliable sources of negatively charged atomic ions is of growing importance for experiments involving antimatter, particularly for studies aimed at producing antiprotonic atoms [1]. In such systems, one of the atomic electrons is replaced by an antiproton. Thus, the use of negative ions enables long-time co-trapping with antiprotons before the formation stage [2].

The presented method of anion production relies on collisions between an electron beam and a molecular beam injected into the trapping region. Because direct attachment of an electron to an isolated atom is inefficient under vacuum conditions, molecular targets are used instead. In dissociative attachment, a molecule can capture an electron in a transient state and subsequently fragment, producing a negatively charged ion. Negative anions can also be created directly (without a transient state) through an electron-molecule collision. To obtain a pure ensemble of atomic anions, diatomic homonuclear molecules are particularly advantageous. In this study, iodine was selected as the primary target because of its high electron affinity, simple isotopic composition, and suitability for forming stable I^- ions. The dissociation of I_2 under electron impact can produce iodine anions with low threshold energy, making this process attractive for efficient ion generation.

The present work reports the design, construction, and experimental testing of a compact, long-lasting source of low-energy atomic anions based on electron-induced dissociative attachment inside a linear Paul trap. The system is intended as a flexible platform for future applications, including integration with the AEGIS experimental infrastructure at CERN [3].

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Photon-blockade breakdown as a first-order dissipative phase transition in zero dimension

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First-order dissipative phase transitions are possible in meso- and even microscopic quantum systems. One of the earliest examples is the photon-blockade breakdown (PBB) effect, which occurs in the driven-dissipative Jaynes–Cummings model describing a prototypical cavity QED system consisting of a bosonic mode coupled to a qubit.

For PBB, an abstract thermodynamic limit has been identified [1], where the coupling g between subsystems increases without affecting the system size, leading to a zero-dimensional phase transition. This limit has been investigated via finite-size scaling, with critical exponents determined numerically [2]. The microscopic mechanism can be understood within a fully quantum treatment and connected to optical bistability through neo- and semiclassical models.

Experimentally, PBB was first observed in a circuit QED system [3], and the thermodynamic limit has been approached using a bespoke superconducting device [4]. Although the system remains microscopic, its behavior becomes increasingly macroscopic as a function of g/κ (κ – cavity linewidth). For the highest realized $g/\kappa \approx 287$, the system exhibits stochastic switching on timescales up to several seconds between a bright coherent state with $\sim 10^4$ intracavity photons and the vacuum state (figure 1), exceeding intrinsic microscopic timescales by several orders of magnitude. Numerical modelling [5] highlights the role of higher transmon levels and phase noise in the dynamics.

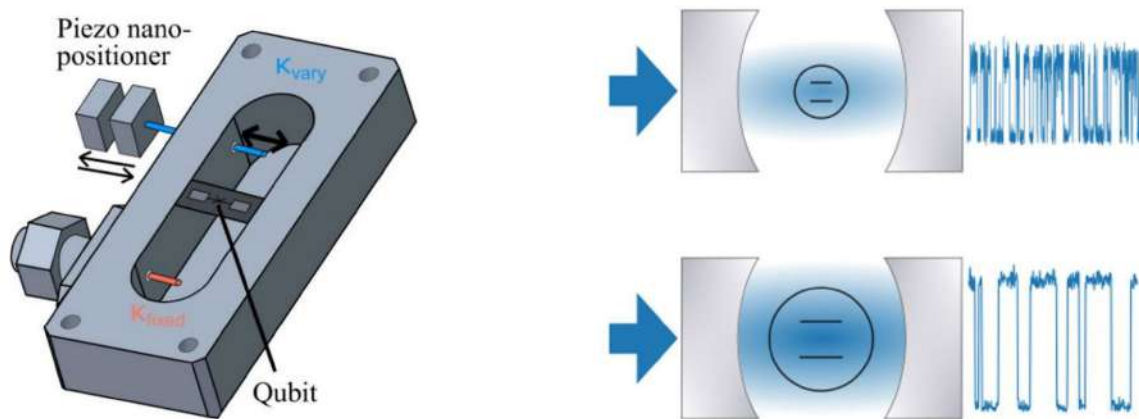


Figure 1: Concept of the photon-blockade breakdown bistability, and the experimental apparatus [4]

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Anomalous diffusion and localization in a disorder-free atomic mixture

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The concept of random walk, in which particles or waves undergo multiple collisions with the microscopic constituents of a surrounding medium, is central to understanding diffusive transport across many research areas. However, this paradigm may break down in complex systems, where quantum interference and memory effects render the particle propagation anomalous, often fostering localization.

In this talk we report on the observation of such anomalous dynamics in a minimal setting: an ultracold mass-imbalanced mixture of two fermionic gases in three dimensions. We release light impurities into a gas of heavier atoms and follow their evolution across different collisional regimes. Under strong interspecies interactions, by lowering the temperature we unveil a crossover from normal diffusion to subdiffusion. Simultaneously, a localized fraction of the light gas emerges, displaying no discernible dynamics over hundreds of collisions. Our findings, incompatible with the conventional Fermi-liquid picture, are instead captured by a model of an atom propagating through a (quasi-)static disordered landscape of point-like scatterers. These results highlight the key role of quantum interference in our mixture, which emerges as a versatile platform for exploring disorder-free localization phenomena.

Directional observation of the superradiant emission of an ensemble of atoms

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Dicke superradiance was predicted in an idealized model in 1954 [1] and observed in a range of experiments [3]. In experiments, the finite size of the sample breaks the symmetry of the idealized Dicke situation. The consequence of this symmetry breaking is that several modes of collective spontaneous emission emerge, defined by Nowak in 2008 [6]. Then, superradiance should occur in one given spatial mode, set solely by the geometry of the sample, resulting in the case of elongated samples in a directionality of superradiant emission [2]. The prediction of the features of the superradiant direction and its emission dynamics in the superradiant cascade is the subject of intense theoretical investigations [5, 4].

Here, we induce superradiance in laser-cooled, two-level atom ensembles. By the use of a high-NA objective lens, for the first time we directly map the light emanating from the cloud (Rb^{87}). We observe that the radiation is split into two contributions, an isotropic background, and one well characterized spatial mode, observed only for superradiant samples. Strikingly, this mode is not a simple Gaussian mode, and matches theoretical expectations for the most superradiant mode of the system obtained by diagonalizing the dissipation matrix.

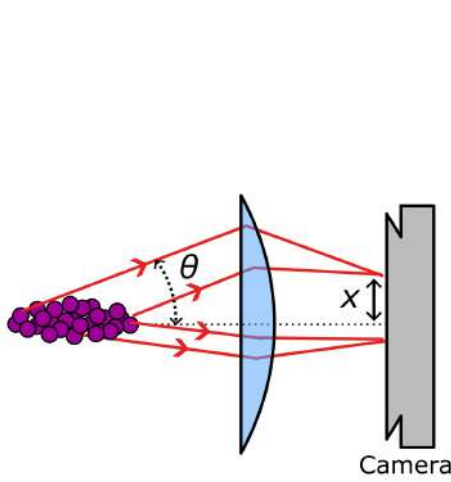


Figure 1: Schematic of the principle of Fourier imaging: allows to map emission directions to positions on a camera.

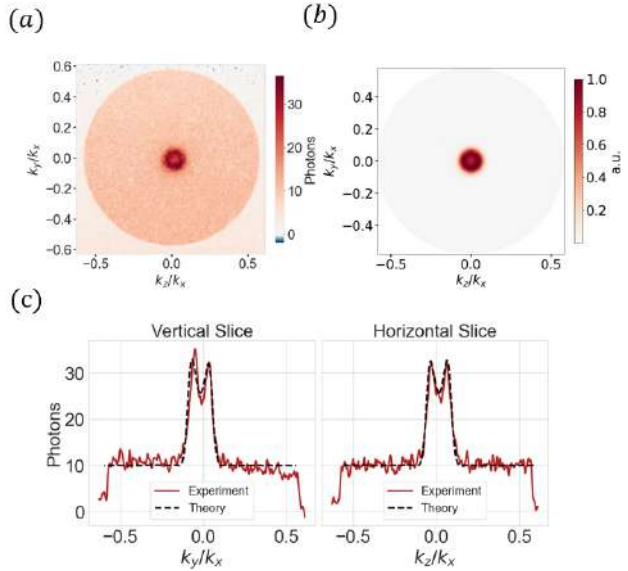


Figure 2: Observation of emission pattern throughout the spontaneous emission of a fully inverted cloud of atoms. (a) Experimental data. (b) Most superradiant mode inferred from the experimental measurement of the cloud size. (c) Comparison of the theory and experiment.

By selecting the light emitted in this mode, we observe that it displays the characteristic features

Many-body quantum phases in programmable light potentials

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Quantum-gas microscopes allow for probing and manipulating many-body quantum systems in optical lattices with single-atom resolution. In these setups, engineered light potentials at the microscopic level can be realized using digital micromirror devices [1]. This technique allows for the creation of arbitrary and highly controllable potentials with single-lattice-site resolution, providing a powerful platform for realizing tailored Hamiltonians, studying disorder and non-trivial lattice geometries.

Using ultracold bosonic atoms in a two-dimensional lattice with a site-resolved, reproducible disorder potential, we identify the Bose-glass phase through in situ measurements of local density distributions and particle-number fluctuations, quantified via the Edwards-Anderson parameter [2]. Using Talbot interferometry, we directly measure the reduced coherence length in the Bose-glass phase (Fig. 1), consistent with the formation of ‘superfluid puddles’. By driving the system across the Bose-glass phase, we further observe signatures of non-ergodic dynamics.

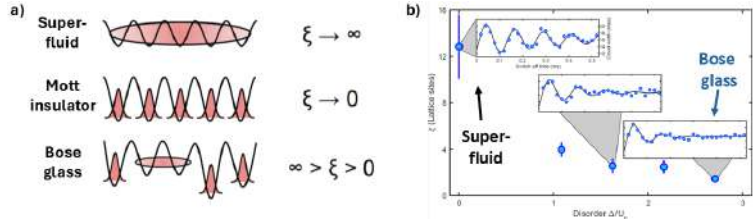


Figure 1: **a)** Phases of the disordered Bose-Hubbard model, showing ‘superfluid puddles’ with reduced coherence length in the Bose-glass phase. **b)** Measured coherence length, ξ , vs disorder strength [2].

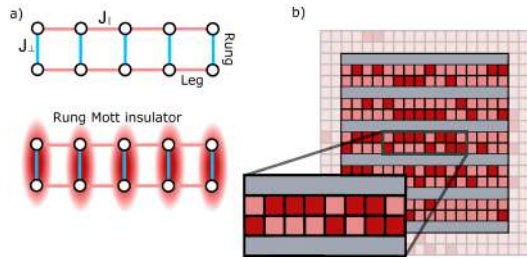


Figure 2: **a)** Two-leg ladder geometry. **b)** Atom occupations, showing the formation of the RMI.

In a second series of experiments, we use repulsive light potentials to separate the system into independent two-leg ladders (Fig. 2), and investigate the Rung-Mott insulator (RMI) - an insulating phase that occurs at half-filling. The phase is identified through site-resolved measurements of the rung parity as a function of inter- and intra-rung tunnelling. We measure the excitation spectrum and compare it to theoretical predictions [3], and further demonstrate that the RMI phase is incompressible.

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A new era of fundamental physics tests with antihydrogen

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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. These trapped ensembles are then used for both spectroscopy [1] and gravitational studies [2].

One of the main limiting factors in the trapping rate of antihydrogen is the positron temperature. By sympathetically cooling the positrons using laser-cooled Be⁺ plasmas, we have recently achieved an eight-fold increase of the antihydrogen trapping rate [3]. A sample of over 15,000 antiatoms can now be produced in under seven hours, enabling high-statistics measurements.

Using Be-assisted antihydrogen production, we have measured the ground-state hyperfine splitting of antihydrogen $a_{1S}/h = 1,420,404.8 \pm 1.1(stat) \pm 5.6(sys)$ kHz in a 1 T magnetic field, consistent with expectations for hydrogen [4]. This 4 parts per million measurement constitutes an improvement over the previous state-of-the-art of two orders of magnitude. At this level our measurement is sensitive to the internal structure of the antiproton, which contributes at about 40 ppm, and is approaching the limit of existing theoretical analyses.

Furthermore, the enhanced trapping rate drives major breakthroughs in laser spectroscopy. While the previous best measurement of the antihydrogen 1S-2S transition was limited to a precision of 2×10^{-12} [1], this development, combined with laser cooling [5] and the implementation of a Cs fountain clock as a local realization of the SI second [6], will bring us much closer to the 4×10^{-15} precision that has been reached in hydrogen [7]. Finally, the larger sample sizes made possible the first observation of the 2S-4P resonance in the antihydrogen spectrum, granting access to fundamental quantities such as the antiproton charge radius.

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Quantum Interference in Identical Particle Collisions

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Collisions between identical ions and their parent atoms are characterized by a fundamental indistinguishability between direct elastic scattering and resonant charge transfer [1]. Because these two distinct physical pathways converge on the same experimental outcome, the total scattering cross-section cannot be described by a classical summation of independent process probabilities. Instead, the wave amplitudes of both channels undergo a coherent superposition, giving rise to pronounced quantum interference that significantly dictate the reaction rates at low collision energies.

We demonstrate this interference effect for the first time by measuring the reaction rates $^4\text{He}^+/^4\text{He}$ and $^3\text{He}^/^3\text{He}$ collisions. By employing a merged molecular beam experiment, we reach the cold temperature regime and utilize velocity map imaging to detect the collision products. We initiate the process with helium Rydberg atoms colliding with ground-state helium atoms to explore the underlying ion-atom interactions. Historically, these interference effects have been neglected because they are less pronounced at high collision energies; however, at the low energies reached in our study, the interference between the elastic and charge-exchange channels becomes significant. Our results first show that accounting for this quantum interference is essential, as neglecting it fails to reproduce the experimentally observed reaction rates.

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Probing weakly bound levels of a Dysprosium atom pair

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Ultracold lanthanide gases, and in particular dysprosium, provide a unique platform for exploring strongly anisotropic magnetic dipolar interactions. Because of their large electronic angular momentum and complex internal structure, these systems exhibit an extremely dense spectrum of Fano--Feshbach resonances arising from the coupling of many collision channels [1-3]. While this spectral density has often been associated with a statistical, chaotic regime [4,5], recent experiments reveal the presence of broad resonances that can be addressed individually.

In this work, we develop a qualitative and quantitative theoretical description of the Fano-Feshbach resonance spectrum in ultracold dysprosium. This work addresses two objectives: (i) to understand the origin of experimentally observed resonances, particularly those associated with very weakly bound molecular states close to the dissociation threshold, and (ii) to identify the dominant mechanisms governing their width, position, and magnetic-field dependence.

Our approach combines accurate long-range interaction potentials, including magnetic dipole-dipole and anisotropic van der Waals interactions, with an effective short-range description based on a single-parameter model. Bound and near-threshold states of Dy₂ are computed using a Mapped Fourier Grid Hamiltonian method. We then calculate Zeeman spectra and compare with the experimental measurements of our colleagues at Collège de France.

By calibrating the short-range parameter to reproduce the last measured bound state, we obtain good agreement with experimental spectra for both ¹⁶²Dy and ¹⁶⁴Dy isotopes, especially for broad resonances associated with very weakly bound states. Our results suggest that these resonances are predominantly controlled by long-range interactions and may be described within a predictive theoretical framework, in contrast with the view of a fully chaotic resonance landscape.

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Order by heating a quantum gas: an unexpected effect

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Recent experiments have shown that raising the temperature of a dipolar gas under certain conditions leads to a transition to a supersolid state [1]. We employ the path integral Monte Carlo method, which exactly accounts for both thermal and correlation effects, to study that phenomenology in a system of ^{162}Dy atoms in the canonical ensemble. Our microscopic description allows to quantitatively characterize the emergence of spatial order and superfluidity, the two ingredients that define a supersolid state. Our calculations prove that temperature, on its own, can promote the formation of a supersolid in a dipolar system [2]. Furthermore, we bridge this exotic phenomenology with the more usual melting of the supersolid at a higher temperature. Our results offer insight into the interplay between thermal excitations, the dipole-dipole interaction, quantum statistics and supersolidity.

Order by heating is also observed in quantum mixtures. We study repulsive two-component Bose mixtures in a finite size box through path integral Monte Carlo simulations [3]. For different values of the s-wave scattering length of the interspecies potential, we calculate, among other physical properties, the polarization of the system at different temperatures. We find two different behaviors: for phase separated states at $T=0$, temperature induces a diffusion effect but, for miscible states at $T=0$, a maximum in the polarization appears at a certain temperature lower than the critical one. In this second case, we can relate this thermal separation to the Bose bunching effect that clusters particles of the same species.

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Small weakly-bound van der Waals clusters studied by Coulomb Explosion Imaging

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Small helium clusters are peculiar few body quantum systems. The helium dimer has a single weakly bound state of a huge spatial extent. About 80% of its probability distribution resides in the classically forbidden tunneling region [1]. We utilize laser-triggered Coulomb explosion imaging for measuring spatial probability distributions and orientation of these quantum objects. Application of an additional laser pulse in a pump-probe manner allows us to observe the structural picosecond response dynamics of small helium clusters upon interaction with a strong laser field. The results on He₂ [2] as well as HeNe [3] dimer will be discussed.

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Cavity-enhanced frequency comb spectroscopy of complex molecules in the long-wave mid infrared

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Complex molecules such as polycyclic aromatic hydrocarbons (PAHs) are thought to be abundant in interstellar matter and are possible carriers of unidentified infrared emission bands. Assignment of specific PAHs remains an unsolved problem, however, partially due to a lack of laboratory reference data. The congested rovibrational structure and often unknown centers of absorption bands of these molecules set strict requirements for spectroscopy: broad spectral coverage, high sensitivity and high resolution. Cooling and low pressures are often required to enable resolution of closely-spaced transitions.

We tackle these challenges with a long-wave mid-infrared (LWIR) cavity-enhanced frequency comb spectrometer setup combined with a 4 K cryogenic buffer gas cell. The instrument provides broadband coverage (6.5–10 μm) with high resolution and sensitivity, while cryogenic cooling reduces Doppler broadening and simplifies the spectra by concentrating the population in low-lying states.

To showcase the capabilities of this instrument, we present spectra of ethane and ethanol with resolved rotational states, measuring absorption linewidths on the order of 18-20 MHz and rotational and translational temperatures of 5.5 ± 0.4 and 10.1 ± 0.5 K respectively for ethane and linewidths of 18-19.5 MHz and translational temperatures of approximately 18-20 K for ethanol [1].

We then extend the measurements to PAHs, reporting spectra near 7 μm for a selection of two-ring PAHs such as naphthalene and azulene, and three-ring, including acenaphthene, acenaphthylene and fluorene. Our preliminary results for PAHs yield linewidths of ~ 10 MHz, corresponding to translational temperatures of ~ 14 K and rotational temperatures of 5-6 K, similar to the ethane measurements, confirming good performance of buffer gas cooling of these molecular systems.

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Metrology of Electromagnetic Fields Using Cold Rydberg Atoms

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Neutral atoms promoted in Rydberg states exhibit extremely large electric dipole moments making them excellently suited for high-precision electric fields measurements. Compared to more conventional antennae, Rydberg based sensors present very interesting characteristics: they are for instance broadly tunable (from the MHz to the THz) while keeping a size independent of the wavelength to be measured. While most of research effort have focused on room-temperature vapor so far, using cold atoms has the advantage of strongly reducing the Doppler frequency broadening, increasing the interaction time between the atoms and the probing beams and offering a better isolation from the environment. We have recently developed a novel approach for microwave sensing based on trap-loss spectroscopy of Rydberg states in a cold ⁸⁷Rb ensemble confined in a Magneto-Optical-Trap. This technique stands out for its simplicity as the detection solely relies on fluorescence measurements. We reported high metrological performance [1] as: a scale-factor linearity at the percent level, no noticeable intrinsic drifts over few hours, leading to a resolution of about $5 \mu\text{V}/\text{cm}$, and the capability to simultaneously measure the amplitude and the frequency of the microwave field.

We will present our latest results in microwave sensing with cold Rydberg atoms. We perform a comprehensive study of noise sources impacting the trap-loss spectroscopy method that lead us to adapt the spectrum probing strategy and improve the linewidth and power stability of both cooling lasers and Rydberg interrogation lasers. This yield significant improvement (see Figure 1), by more than an order of magnitude, in the sensor performance in terms of sensitivity, linearity and long term stability. We will also discuss mid-term objectives of this experiment: sequencing the atom interrogation allows to avoid the spurious effect of the cooling light and takes advantage of cold atoms by approaching the Doppler limit ; trapping and manipulating the atoms in an array of optical tweezers will allow to explore new operational regimes to enhance the spatial and spectral resolution of the sensor and harness the atom-atom interactions together with quantum metrology protocols to potentially implement quantum multi-parameter estimation.

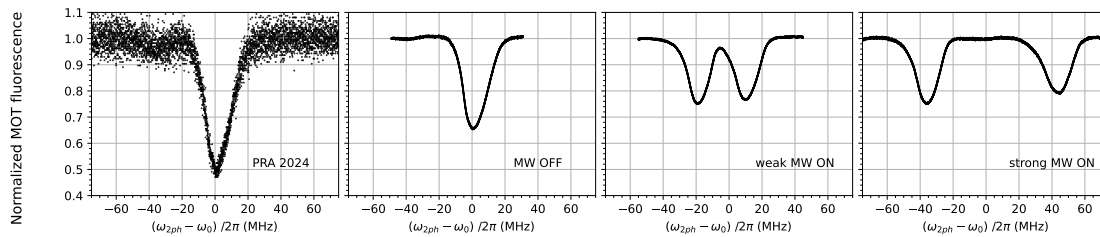


Figure 1: From left to right: published trap-loss spectrum of a ground to Rydberg transition [1]; same spectrum with an improved signal-to-noise ratio; Autler-Townes splitting spectra with increasing microwave power.

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Ultra-High-Resolution Mid-Infrared Spectroscopy using Sub-Hz Stabilized Quantum Cascade Lasers: towards Tests of Fundamental Physics

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We report accurate, high-resolution mid-infrared (MIR) spectroscopy of methanol and ethylene near 10 μm using ultra-stable quantum cascade lasers (QCLs) stabilized to SI-traceable optical frequency references. In the first setup, the QCL was phase-locked to a 1.54 μm optical reference – provided by the national fiber-optic metrology network [1] and calibrated to the atomic clocks of the French time-frequency metrology institute – via a mode-locked optical frequency comb, yielding a linewidth of ~ 0.1 Hz at 1 s and 1 GHz tunability [2]. Ethylene and methanol spectroscopy was performed using frequency-modulation cavity-enhanced saturated absorption, providing line-center uncertainties 2 to 3 orders of magnitude smaller than those in the HITRAN database. Notably, we achieve a statistical uncertainty of 57 Hz and a systematic uncertainty of 437 Hz for the ($J', K_a', K_c' = 9, 2, 8$) - ($J'', K_a'', K_c'' = 9, 3, 6$) ethylene transition. Instrumental limitations and molecular lineshapes were also analyzed. These results can significantly improve molecular databases. In addition, accurate methanol measurement opens the possibility for direct comparison to high-resolution astronomical spectra to probe possible variations of the electron-to-proton mass ratio (m_e/m_p) over cosmological timescales [3]. To extend the frequency tuning range, in the second setup the QCL was phase-locked to a CO₂ laser stabilized to an OsO₄ transition - the secondary frequency standard in the MIR region - resulting in a linewidth of ~ 10 Hz. A novel ultra-broadband quantum well infrared photodetector (QWIP) [4] was employed to detect the QCL/CO₂ beat note at tens of GHz, allowing wide frequency tuning around CO₂ laser emission lines. We demonstrated a 10 GHz continuous scan of an ultra-stable QCL and exploited this to record Doppler-broadened methanol rovibrational lines at room temperature. This wide tuning range of a phase-locked QCL extends the toolbox for precision metrology in the MIR region. Future developments combining fast MIR detectors, modulators [5], and sub-Hz QCLs will aim to achieve ultra-accurate, widely tunable vibrational spectroscopy across the molecular MIR fingerprint region, enabling stringent tests of fundamental physics, including parity violation in chiral molecules [6] and variations of m_e/m_p [3].

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Quantum squeezing of the motion of a levitated nanoparticle

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Optical levitation of solid micro- and nanoparticles in an optical tweezer has been an important tool to study single-particle nonequilibrium dynamics in a wide variety of fields. Recent advances in cooling the motion of a single nanoparticle in vacuum to the ground state of its trapping potential open up intriguing possibilities of exploring quantum mechanical behaviors at a macroscopic scale. In this talk, I will discuss experimental progress in achieving quantum squeezing of the motion of a levitated nanoparticle, which is a first realization of its non-classical motion [1].

An experimental system closely related to levitated nanoparticles is ultracold atoms in an optical trap, where a crucial technique to reveal their quantum behaviors has been to measure their momentum distribution through time-of-flight free expansion of their wavefunction. An important prerequisite for ensuring reliable time-of-flight measurements is that the particles are charge-neutral and are uninfluenced by any stray fields.

We developed an all-optical approach for cooling the center-of-mass motion of a levitated nanoparticle in an optical lattice to the ground state [2]. We found that the center-of-mass motion is coupled to librational motions due to the asymmetric geometry of the nanoparticle. Such coupling implies significant broadening of the velocity distribution through angular motions. We developed a model to understand librational motions in an optical lattice and realized feedback cooling of all the librational motions simultaneously with three translational motions [3]. When librational motions are suppressed by feedback cooling, the time-of-flight measurements for a levitated nanoparticle provide the velocity distribution consistent with the motional temperature [4].

Rapid modulation of the trapping potential has been used to manipulate the uncertainties of a harmonic oscillator and achieve quantum squeezing. We rely on this approach to reduce the velocity variance of a trapped nanoparticle to below the zero-point fluctuation by around 5 dB, which is confirmed by time-of-flight measurements [1]. Furthermore, we use an optical lattice as a reliable reference to validate the calibration of the position signal. Our demonstration of quantum squeezing forms an important basis for future studies in quantum sensing of weak forces and investigating quantum mechanics at a macroscopic scale. Taking advantage of the reduced uncertainty achieved with a rapid potential control, we have recently demonstrated static force sensing below the zero-point fluctuation [5,6].

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Dynamics of coupled spin ensembles in a K–Rb–³He comagnetometer

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Atomic comagnetometers, based on coupled spin ensembles of alkali-metal and noble-gas atoms, have emerged as powerful tools for precision measurements and searches for physics beyond the Standard Model [1]. By exploiting spin-exchange interactions in dense atomic vapors, these systems enable suppression of magnetic field noise while retaining sensitivity to non-magnetic spin-dependent interactions [2].

Recent work with a self-compensating Rb–K–³He comagnetometer has demonstrated its applicability to searches for ultralight dark matter within the Global Network of Optical Magnetometers for Exotic physics searches [3, 4]. At the same time, such systems provide a broader platform for engineering spin interactions via Floquet modulation of magnetic fields. In particular, parametric modulation enables control of the effective coupling between electron and nuclear spins, allowing access to regimes characterized by long-lived nuclear coherence and tunable interaction strength [5].

Beyond sensing applications, this controllability opens a route to exploring non-Hermitian dynamics in hybrid spin systems. Exceptional points arise naturally in this platform and lead to an enhanced, fractional power-law response to external perturbations. However, despite this enhanced response, no corresponding improvement in signal-to-noise ratio is observed, pointing to fundamental limitations of exceptional-point-based sensing in this system.

In this talk, I will review experimental work performed in a Rb–K–³He vapor mixture that extends beyond the conventional use of comagnetometers for non-magnetic sensing. I will present the experimental realization of a second-order exceptional point and discuss its implications for precision magnetometry.

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Chiral Recognition with High-Energy Photo- and Compton Electrons

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Molecules, whose mirror images (called enantiomers) are not congruent with each other by translation or rotation, are chiral. Recognizing enantiomers is of high biological and chemical relevance [1]. Coulomb explosion imaging is a capable, yet limited, method for this purpose. Alternatively, employing high-energy electrons enables imaging of the molecular structure by electron diffraction. Here, we show the ability of chiral recognition by combining these two techniques [2]. For this purpose, we consider the ionization of the O 1s orbital of methylorixane molecules by photoionization and by Compton scattering of 20 keV photons (figure 1). The resulting momentum distributions show double-slit-like interference patterns (blue and white circles) [3]. Additionally, main lobes (red high intensity spots) from the emitting oxygen toward the carbon atoms appear in the angular distributions. The lobe at $\phi \approx 135^\circ$, which is above the plane for one enantiomer and below for the other, can be used to recognize chirality. Our results extend the photon spectrum, used for chiral recognition, into the hard x-ray domain.

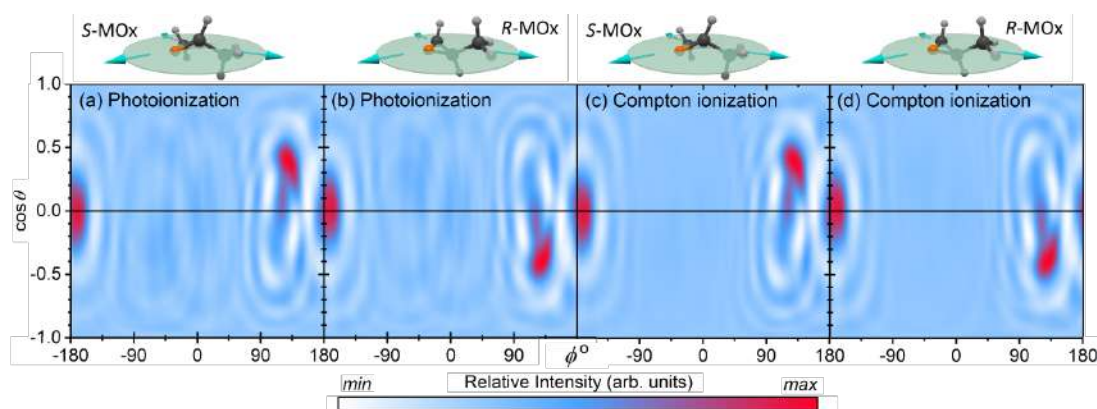


Figure 1: Results from our work [2]. Polarization averaged photoelectron (a),(b) and photon-momentum-transfer averaged Compton electron (c),(d) molecular frame angular distributions for the O 1s ionization of methyloxirane's S- (a),(c) and R- (b),(d) enantiomers (see insets), evaluated for the electron kinetic energy of 400 eV. For the alternated enantiomers, the electron angular distributions are mirrored with respect to the horizontal line at $\cos \theta = 0$, which corresponds to the green plane in the insets.

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A universal approach to saddle-point methods in attosecond science

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Light-matter interactions in the strong-field regime, such as high-harmonic generation (HHG), typically give rise to highly-oscillatory integrals, which are often solved using saddle-point methods. Not only do these methods promise a faster computation, but they also inform a more intuitive understanding of the process in terms of quantum orbits, as the saddle points correspond to interfering quantum trajectories (i.e., Feynman's path integral formalism). Despite these advantages, a sound understanding of how to rigorously apply saddle-point methods to highly-oscillatory integrals in high dimensionality with algorithms that work uniformly for arbitrary configurations and laser fields, remains conspicuously absent. This hinders our ability to keep up with state-of-the-art experimental setups which increasingly rely on tightly-controlled laser waveforms.

We introduce the key ideas of Picard-Lefschetz theory — the foundation of all saddle-point methods — and their implementation. Using HHG and above-threshold ionisation driven by two-colour laser fields as examples, we show how those ideas provide a universal and robust approach for a fast computation of the integrals, as well as a widely-applicable algorithm to derive the relevant semi-classical quantum orbits that underlie the physical processes. We demonstrate this for setups that involve spectral caustics, as well as intensity scans for a two-colour field beyond the perturbative regime (“colour switchover”), which were previously rendered impossible to solve with saddle-point methods due to coalescences and branch cuts.

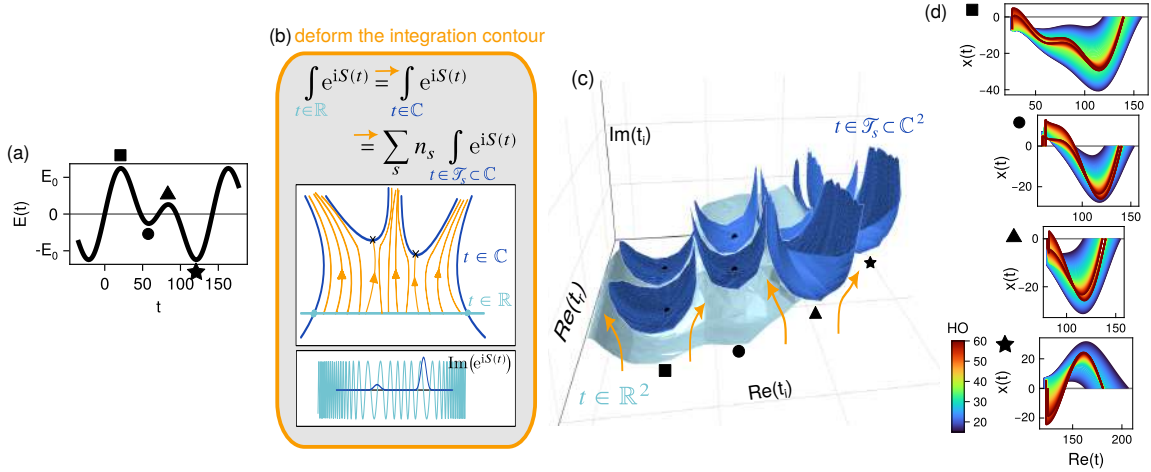


Figure 1: For arbitrary driving fields (panel (a)) we can solve time integrals by deforming the integration contour from the real into the complex domain, so as to minimise oscillations of the integrand (b). In the case of HHG we integrate over ionisation and recombination times, hence the deformed contour is embedded in $\mathbb{C}^2$. A projection in $(\text{Re}(t_i), \text{Im}(t_i), \text{Re}(t_r))$ for harmonic order 25 generated from the shown field is in (c), and the corresponding electron trajectories for a range of harmonic orders in (d).

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Programming quantum optical simulators

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In this talk, I will review some of my recent works [1, 2, 3, 4] on how to harness the recent experimental advances in programmable AMO simulators based on fermionic ultra-cold atoms, Rydberg atomic arrays or waveguide/cavity QED.

First, I will briefly show how the tunable-range interactions appearing in waveguide or multi-mode cavity QED can be used to construct wavefunction ansätze that approximate the ground state of quantum spin models [1, 2].

Second, I will discuss several "programmable" protocols [3] for improving ground-state preparation with ultra-cold atoms beyond adiabatic approaches, and apply them to local and extended Fermi-Hubbard models with and without doping.

Finally, I will discuss an algorithm specifically tailored for analog quantum simulators that use data gathered from the device to accurately investigate properties of the ground state of spin and Fermi-Hubbard Hamiltonians [4].

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Optimal control of mechanical systems in the quantum regime

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Continuous-variable quantum systems enable encoding complex states in fewer modes through large-scale non-Gaussian states. Motion, as a continuous degree of freedom, underlies phenomena from Cooper pair dynamics to levitated macroscopic objects. Hence, realizing high-energy, spatially extended motional states remains key for advancing quantum sensing, simulation, and foundational tests. In the talk, I will present the following control tasks for various nonlinear mechanical systems, including trapped atoms, levitated particles, and clamped oscillators with spin-motion coupling. (i) **Non-harmonic potential modulation**: Optimal control of a particle in a nonharmonic potential enables the generation of non-Gaussian states and arbitrary unitaries within a chosen two-level subspace [1, Fig. 1(a)]. (ii) **Macroscopic quantum states of levitated particles**: Rapid preparation of a particle's center of mass in a macroscopic superposition is achieved by releasing it from a harmonic trap into a static double-well potential after ground-state cooling [2, 1(c)]. (iii) **Phase-insensitive displacement sensing**: For randomized phase-space displacements, quantum optimal control identifies number-squeezed cat states as optimal for force sensitivity under lossy dynamics [3, 4, 1(b)]. These approaches exploit either intrinsic nonharmonicity or coherent nonlinear coupling, providing a unified framework for motion control in continuous-variable quantum systems—from levitated nanoparticles to optical and microwave resonators—paving the way toward universal quantum control of mechanical degrees of freedom.

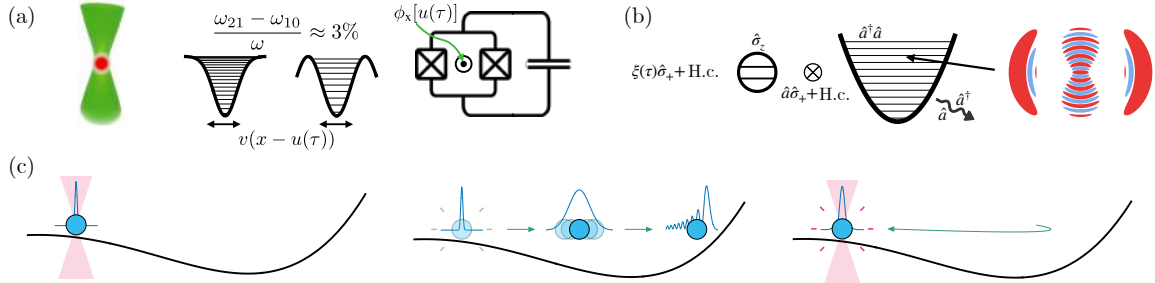


Figure 1: (a) Examples of continuous nonlinear systems that can be optimally controlled without the need of auxiliary systems—single atoms in optical tweezers and flux-tunable transmons. (b) In an optimally controlled spin-boson model with finite controllability and decoherence, a family of number-squeezed cat states maximizes achievable sensitivity for weak force sensing. (c) The protocol for the preparation of a macroscopic quantum state of a nanoparticle utilizing hybrid potential.

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Microwave dressed Rydberg atoms coupled through a single-photon transition to a superconducting coplanar waveguide resonator

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Interfacing Rydberg atoms with chip-based superconducting coplanar waveguide (CPW) microwave resonators provides a promising route for networking neutral atom and superconducting quantum processors [1–4]. In this setting, vacuum Rabi oscillations of $2\pi \times (1 - 10)$ MHz are expected for a single Rydberg atom positioned $10 - 50 \mu\text{m}$ above the surface of a superconducting coplanar waveguide (CPW) resonator. Such an interface would allow, e.g., optical addressing of superconducting qubits with light at telecom wavelengths in an interaction mediated by the atom.

Here, we report interfacing He Rydberg atoms in a beam with the 11.752 GHz mode of a niobium nitride CPW resonator using the single-photon $1s50s^3S_1 \rightarrow 1s50p^3P_J$ transition [5]. This represents the first demonstration of coupling a superconducting CPW resonator to a single-photon Rydberg transition with a large electric-dipole moment ($1500 ea_0$) in near-zero dc electric field. To achieve this, a microwave dressing field (see Figure 1), detuned from the $1s50p^3P_J \rightarrow 1s50d^3D_J$ transition, was used to shift the $1s50s^3S_1 \rightarrow 1s50p^3P_J$ transition into resonance with the resonator mode through the AC Stark effect. This approach allowed the microwave power in the resonator to be reduced by more than 2 orders of magnitude compared to previous work, with an estimated single-photon coupling strength of $2\pi \times 100$ Hz. To reach the strong-coupling regime in this hybrid cavity QED setting, it is now necessary to increase the atom-resonator interaction time. To this end, we have upgraded our apparatus to incorporate a cryogenic source of metastable He compatible with frequency-chirped laser slowing. These recent advances will also be summarized.

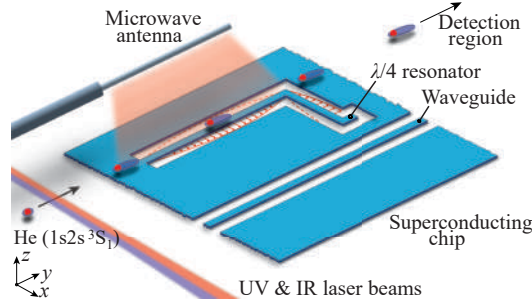


Figure 1: Schematic diagram of microwave dressed Rydberg-atoms at the interface with superconducting circuit.

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Light interactions with polar quantum systems

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The optical response of atomic and molecular systems is typically governed by transition dipole moments, which encode spatial symmetries and enforce selection rules. In contrast, permanent dipole moments are usually associated only with static energy shifts and are neglected in coherent dynamics. Here we show that in driven systems with broken inversion symmetry, permanent dipole moments qualitatively modify both emission processes and light–matter coupling, giving rise to regimes beyond standard quantum optical models.

In such polar systems, laser-driven population transfer between states with nonzero diagonal dipole matrix elements generates an additional time-dependent dipole moment, leading to coherent emission at the Rabi frequency [1, 2, 3]. Since this frequency is set by the driving field rather than the bare transition, it enables all-optical tunability over a wide spectral range. Importantly, this mechanism does not rely on population inversion and persists in open-system dynamics.

At the same time, permanent dipole moments fundamentally alter the structure of the light–matter interaction. In the strong-field regime, their contributions may become comparable to transition dipole coupling, resulting in a nonlinear dependence of the effective Rabi frequency on the driving field amplitude. This leads to a renormalization of both the transition frequency and coupling strength, marking a breakdown of the linear-response and rotating-wave approximations [4, 5]. As a consequence, the modified coupling can stabilize coherent dynamics in the presence of strong spatial inhomogeneities of the driving field, providing new routes for maintaining coherence in realistic media [6].

Finally, we identify a distinct regime in which permanent dipoles couple directly to the driving field without inducing transitions, thereby modifying the system-reservoir interaction. In the single-photon regime, this leads to suppression of spontaneous emission, while in the semiclassical limit it results in its enhancement and enables otherwise forbidden processes, such as reservoir-induced excitation of the atomic state–spontaneous absorption [7].

These results establish permanent dipole moments as an active resource in quantum optics and open pathways toward controllable light–matter interaction in symmetry-broken systems.

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Coherent measurements of the (anti)proton magnetic moment at BASE-CERN

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The Baryon Antibaryon Symmetry Experiment (BASE) is dedicated to conducting ultra-precise tests of Charge-Parity-Time (CPT) invariance by comparing the intrinsic properties of protons and antiprotons, such as their charge-to-mass ratios, lifetimes, and magnetic moments. In this presentation, I will summarize our recent progress and achievements, focusing on the experiment at CERN, which since 2022 has been dedicated to achieving a 10- to 100-fold improvement in measurements of the proton and antiproton magnetic moments. To date, we have determined these quantities with fractional uncertainties of 1.5 parts per billion for the antiproton [1] and 300 parts per trillion for the proton [2].

To achieve these improvements, we developed and successfully implemented non-destructive spin-state spectroscopy of single nuclear spins [3]. We have achieved a spin coherence time of 50 seconds and gained precise control over the linewidth of the g-factor resonance, which, from this perspective, should enable an at least 100-fold improvement in the determination of the g-factor. So far, limited by cyclotron-frequency fluctuations, we have measured a g-factor resonance with a width corresponding to a coherence time of about 10 seconds, representing a sixteen-fold reduction in spectral linewidth, compared with our previous measurements. The result is still in preparation due to ongoing systematic studies, slowed down by magnetic noise present in CERN's AD/ELENA facility. Recently, we further upgraded the experimental apparatus to fully exploit the 50-second coherence time and to further improve fractional resolution, having in mind a CERN Long Shutdown starting in September 2026, which will allow us to perform 1.5 years long precision measurement campaign.

Additionally, I will discuss recent developments in (anti)proton transport [5], which will enable the transfer of antiprotons to external offline laboratories, thereby reducing environmental disturbances and further improving measurement precision.

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VUV-UV-VIS FT spectroscopy and the first observation of interference between indirect interaction pathways in CO

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Diatomic molecules continue to play a central role in high-resolution spectroscopy, astrophysics, and exoplanetary science, where reliable molecular line positions and intensities are essential for the identification and quantitative analysis of species in planetary and interstellar environments [1]. Carbon monoxide is particularly important because its isotopologue-dependent spectra provide sensitive probes of chemical evolution in interstellar clouds and stellar atmospheres [2].

To obtain accurate spectroscopic information, we combine two complementary FT techniques: VUV absorption spectroscopy (SOLEIL synchrotron) [3] and UV-VIS emission spectroscopy (University of Rzeszów) [4]. The observed CO spectra were analysed by a multistate deperturbation treatment based on effective-Hamiltonian modelling and a simultaneous fit of molecular constants and term values [5,6]. This approach yields a consistent description of the rovibronic level structure in the presence of extensive direct and indirect unimolecular interactions.

Particular attention is devoted to the nominally very weak direct $A^1\Pi - a^3\Pi$ interaction between near-degenerate rovibronic levels belonging to electronic states of the same valence configuration. Because of the extremely small vibrational overlap integral, $\langle a^3\Pi, v' | A^1\Pi, v'' \rangle \approx 10^{-5} - 10^{-6}$, this interaction would be expected to remain undetectable. However, measurable level shifts and clear intensity signatures indicating this perturbation are found in $^{13}\text{C}^{18}\text{O}$. These observations led us to investigate, for the first time in CO, interference between indirect perturbation pathways, providing a new perspective on the origin of unexpectedly strong spectroscopic effects in multiply perturbed rovibronic manifolds.

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New experimental approaches to high-precision studies of molecular hydrogen ions

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Precision spectroscopy of molecular hydrogen ions (MHIs) enable tests of quantum electrodynamics (QED), determinations of fundamental constants (FCs), and searches for physics beyond the Standard Model (BSM) [1]. We have recently investigated the future potential of this field and shown that ultra-high-precision spectroscopy of a suitable subset of transitions across different isotopologues of MHIs, combined with hydrogen and deuterium spectroscopy, enables the extraction of several FCs with substantially improved precision [2, 3]. Under realistic assumptions, the uncertainties in the proton-, deuteron-, and triton-to-electron mass ratios, as well as the triton radius, can be reduced by more than two orders of magnitude relative to the CODATA 2022 values. This approach would also enable determinations of the proton and deuteron radii using purely electronic systems, with uncertainties competitive with those obtained from muonic hydrogen and deuterium spectroscopy. Consequently, it would provide a stringent test of lepton universality in the low-energy regime.

Here, we will report about two important advances in the field. First, we succeed to perform the first laser spectroscopy of H_2^+ , achieving fractional frequency uncertainty of 8×10^{-12} [4]. From a combined experimental and theoretical analysis, we obtain an improved value of the proton-to-electron mass ratio with a relative uncertainty of 2.5×10^{-11} , in agreement with Penning-trap mass spectrometry but with a 2.3-fold smaller uncertainty. The observed agreement between theory and experiment at the 8.1×10^{-12} provides a validation of three-body quantum theory. This experiment constitutes a significant step toward a CPT-symmetry test via comparison of a rovibrational transition in H_2^+ and its antimatter counterpart $\bar{\text{H}}_2^-$ [5, 6, 7].

Second, we investigate the validity of QED predictions for the hyperfine structure in MHIs by resolving the ground-state hyperfine structure of HD^+ . Full resolution is achieved by exploiting doubly spin-forbidden transitions within a rotational manifold. This allows us to determine the hyperfine Hamiltonian coefficients with unprecedented precision. The extracted values improve previous results by up to three orders of magnitude and are in excellent agreement with state-of-the-art theoretical predictions [8].

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Photoionization attosecond dynamics from molecules of increasing size

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Ionization with a single photon is one of the most fundamental processes in physics. The photoelectric effect describes the photon energy that liberates an electron. However, classically, before being liberated into the continuum, the electron interacts with its parent atomic potential. This scattering can semi-classically be interpreted in the temporal domain as an ionization delay that usually falls in the attosecond timescale [1,2,3].

Most of the works in the field of attosecond physics have been devoted to atoms or small molecules near resonances *i.e.* where high ionization time delays are expected. New questions arise when the size of the molecule increases [3,4]. Classically, the ionization time delay may increase with the size of the scattering potential *i.e.* the size of the molecule [5]. Recently, we have shown that this delay strongly depends on the geometry of the molecule. By comparing many-atom molecules of similar size and composition (C_xH_y), but different geometries (spherical vs. planar), we found that 2D molecules have a strong quadrupole contribution that leads to a significant negative ionization time delay. To illustrate the process, measurements and calculations were performed in naphthalene, pyrene, fluorene and compared with adamantane at different photon energies. The results match with a simple quantum scattering model that unravel the underlying physics [6].

To measure the ionization phase, a second pulse is required and it also adds a phase term into the wavefunction. This additional phase term is usually described by an hydrogenic model [7], also used for small molecules. Recently, we proposed a general solution that consists in tabulating the transition dipoles with partial waves resolution. The implementation of such transitions is straightforward from the XUV transition dipole matrix elements, and intrinsically contains the angular resolution. The accuracy of the method has successfully been compared with the full simulation and experimental measurements [8].

Attosecond dynamics can also be accessed through time-resolved XUV absorption spectroscopy that combines high temporal and spectral resolution [9]. We will present such experiments under development in our group. Our preliminary results are in agreement with the literature [10] and the perspectives will be discussed.

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Experimental Generation of Many-Body W States via Topological Frustration in Rydberg Quantum Simulators

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W states represent a paradigmatic class of multipartite entangled states, characterized by the coexistence of robust bipartite and genuinely multipartite correlations, making them a valuable resource for quantum information processing and quantum algorithms. In this talk, I will present a protocol for the deterministic preparation of W states based on the concept of topological ring frustration in many-body systems. The method is experimentally implemented on a programmable array of Rydberg atoms, achieving the generation of W states with up to 11 qubits encoded in Rubidium atoms.

I will discuss the scalability of the protocol, supported by numerical simulations indicating favorable performance for systems comprising several tens of qubits within near-term technological capabilities. Particular emphasis will be placed on the validation of the prepared states: we introduce an efficient fidelity estimator requiring only two measurement settings, enabled by a novel Bayesian quantum state tomography framework that leverages classical numerical simulations to mitigate experimental limitations.

The experimentally obtained lower bound fidelity of approximately 77% for the 11-qubit state demonstrates the reliability of the approach. Overall, this work establishes a concrete pathway for the generation and certification of high-quality multipartite entanglement in quantum simulators, highlighting how many-body physics and topological effects can be harnessed to advance quantum technologies and achieve quantum advantage.

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Quantum noise scaling in continuously operating multiparameter sensors

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We experimentally investigate the quantum noise mechanisms that limit continuously operating multiparameter quantum sensors. Using a hybrid rf–dc optically pumped magnetometer, we map the photon shot noise, spin projection noise, and measurement back-action noise over an order of magnitude in probe power and a factor of three in pump power while remaining quantum-noise-limited. We observe linear, quadratic, and cubic scaling of the respective total noise powers with probe photon flux, together with a quadratic dependence of back-action on pump photon flux, in quantitative agreement with a stochastic Bloch-equation model. At higher probe powers, additional probe-induced relaxation modifies the spin-noise spectrum while preserving the integrated noise scaling. Our results reveal fundamental, resource-dependent trade-offs unique to continuously monitored multiparameter sensors and establish experimentally the quantum limits governing their optimal operation.

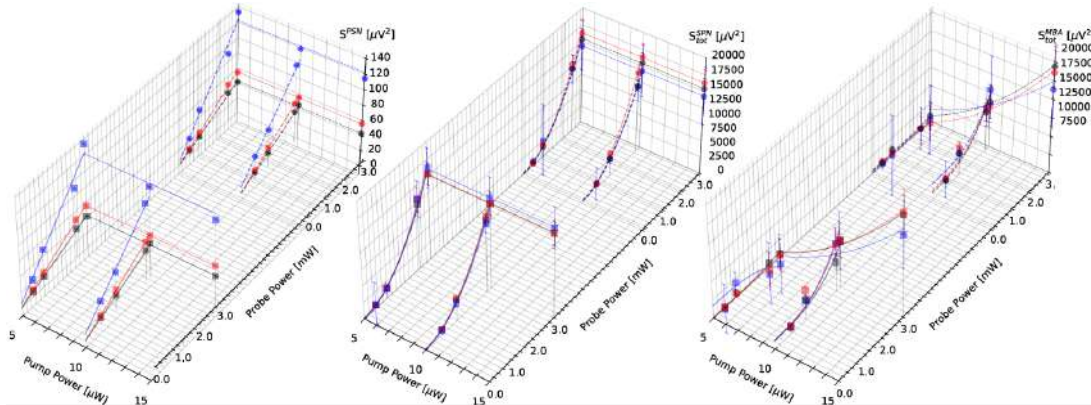


Figure 1: Quantum noise scaling with probe and pump power. Measurements are shown for the DC channel (squares, solid fits) and RF channel (circles, dashed fits), using coherent (red), squeezed (black), and antisqueezed (blue) probe light. Left: Photon shot noise (PSN) power spectral density shows linear scaling with probe power and no dependence on pump power. Middle: Total spin projection noise (SPN) power for an unpolarized ensemble shows quadratic scaling with probe power and no dependence on pump power. Right: Total measurement backaction (MBA) noise power for polarized ensembles shows cubic scaling with probe power and a quadratic dependence on pump power.

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Theoretical investigation of charge recombination processes involving the BH reaction complex relevant for fusion plasmas

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Rate coefficients for collision processes involving boron-containing species are required for the modeling of fusion plasmas in devices such as ITER. The first wall of the vacuum chamber is made of tungsten. This will be coated with a thin boron layer in order to reduce impurity influx into the plasma and thereby minimize radiation losses. The present theoretical investigation was initiated within a Coordinated Research Project organized by the IAEA [1], with the goal to study scattering processes involving the BH reaction complex and its isotopologues.

In this work, we investigate dissociative recombination: $\text{BH}^+ + \text{e}^- \rightarrow \text{BH} \rightarrow \text{B} + \text{H}$,
as well as mutual neutralization: $\text{B}^+ + \text{H}^- \rightarrow \text{BH} \rightarrow \text{B} + \text{H}$ [2].

Both processes proceed through electronically excited states of the BH reaction complex. Advanced MRCI quantum chemistry calculations are combined with fixed-nuclei electron scattering calculations to determine adiabatic potential energy curves, non-adiabatic couplings, and autoionization widths of resonant states. The electronic states are subsequently transformed into diabatic representations, and the nuclear dynamics are treated quantum mechanically [3-4]. Figure 1 shows the potential energy curves of BH electronic states with $^3\Delta$ symmetry. This symmetry is found to play an important role in low-energy dissociative recombination.

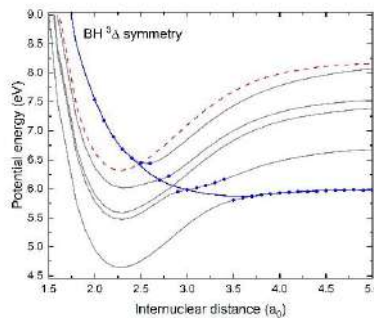


Figure 1: Adiabatic potential energy curves of BH in $^3\Delta$ symmetry. The blue curve shows the potential of a resonant state important for dissociative recombination. The red dashed curve is the BH^+ potential.

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Polarizability measurements employing Yb^+ and Sr^+ optical clocks for systematic uncertainties below 10^{-18}

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Optical frequency standards based on blackbody radiation (BBR)-insensitive transitions claim fractional uncertainties below 10^{-18} [1,2]. In many optical clocks operated at room temperature the shift induced by BBR imposes the largest correction to the clock frequency and limits the systematic uncertainty to 10^{-18} , due to the uncertainty in the differential scalar polarizability $\Delta\alpha$.

To achieve sub- 10^{-18} systematic uncertainty for the $^2\text{S}_{1/2} (F=0) \rightarrow ^2\text{F}_{7/2} (F=3)$ electric octupole (E3) transition in $^{171}\text{Yb}^+$, we are determining $\Delta\alpha$ by perturbing the clock ion with an infrared (IR) laser. Current $\Delta\alpha$ measurements obtained by scanning an IR beam across a single ion achieve fractional uncertainties of $\approx 2\%$ [3,4].

Since $\Delta\alpha$ of the $^2\text{S}_{1/2} \rightarrow ^2\text{D}_{5/2}$ transition in $^{88}\text{Sr}^+$ is known with an uncertainty of 0.04 % from a measurement that balances Doppler and Stark shifts due to the radiofrequency (RF) trapping field [5], we calibrate an IR laser intensity by measuring its induced Stark shift on $^{88}\text{Sr}^+$. Applying this calibrated field to $^{171}\text{Yb}^+$ allows us to extract $\Delta\alpha$ for the E3 transition with an uncertainty of 0.3 %, limited by tensorial contributions. This approach, analogous to [6,7], enables a BBR shift uncertainty reduction for the E3 clock transition to well below 10^{-18} .

For comparison, we extract $\Delta\alpha$ for $^{88}\text{Sr}^+$ using the calibrated IR laser intensity as well, in the same manner as in [3,4]. The two techniques yield results that differ by 15(2) %, indicating an unrecognized offset. These findings underscore the necessity of cross validation among $\Delta\alpha$ measurement techniques before adopting them for BBR shift corrections. For this purpose, we plan to measure $\Delta\alpha$ by changing the environment temperature directly as a third independent method.

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Rydberg thermometry in a Strontium Optical Lattice Clock

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

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

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

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Quantum and classical computing with optical neural networks

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The past decade has witnessed remarkable developments in machine learning and artificial intelligence applications across both research and industry. However, this progress comes at the cost of high energy consumption required to process massive amounts of data. Data centers already consume an estimated 1.5% of global electricity, with a rapid increase predicted in the coming years, driven largely by the demands of AI. As the performance of complementary metal-oxide semiconductors (CMOS) no longer follows Moore's law, substantial research has focused on finding alternative information processing platforms characterized by high performance and energy efficiency. Consequently, optical neural networks have attracted significant interest [1]. Photonic information processing offers high speed, massive parallelization, low communication losses, and high bandwidth, and fully functional photonic neural networks have already been realized in laboratory settings.

We consider the advantages of optical neuromorphic computing, focusing particularly on its potential to outperform electronic systems in terms of energy efficiency, speed, and latency. We investigate both all-optical and optoelectronic systems to demonstrate their computational advantages, accounting for both theoretical performance limits and scalability. Specifically, we discuss exciton-polariton light-matter systems as a powerful platform for all-optical nonlinear information processing [2].

Unlike classical machine learning, quantum computing has not yet matured into a widespread technology, though its potential to accelerate practical computations is considered far-reaching. Physical quantum machine learning (QML) represents a lesser-known but promising path toward quantum advantage that is, in principle, applicable to arbitrary machine learning tasks. We demonstrate the experimental implementation of a quantum neural network on an integrated photonic chip excited by single-photon sources [3]. This setup enables the execution of quantum tasks that are, by definition, inaccessible to classical systems, such as quantum state tomography.

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Coherent dynamics in an ensemble of warm atoms at optical frequencies

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Coherent dynamics is of paramount importance for experimental quantum optics and for the vast majority of applications employing light-matter interaction. Most experiments rely on cold atoms in order to suppress decoherence introduced by Doppler broadening. Only a few experiments have demonstrated coherent dynamics of electronic populations on optical transitions in warm atoms, but with the excitation Rabi frequency exceeding the Doppler broadening bandwidth [1, 2].

We report on the first observation of coherent dynamics in an ensemble of warm, Doppler-broadened atoms, with Rabi frequencies much lower than the Doppler broadening. This is achieved by operating in the regime of moderate saturation $s \approx 1$ and Rabi frequency $\Omega_R > \Gamma$, where a velocity selective excitation mechanism leads to the interaction with only a subset of velocity classes of resonant atoms, which corresponds to a narrow distribution of effective Rabi frequencies. The experiment operates in the effectively two-level atom limit of ^{87}Rb , stored in bulk 7 cm-long vapor cell.

The measurements of the spectral distributions of the resonance fluorescence allow for the observation of the clear Mollow triplet in the continuous excitation regime. Under the pulsed excitation, the corresponding Rabi oscillations can be clearly resolved. The dominant decoherence mechanism is the excited state population decay and residual Doppler broadening, which sets the upper limit on the coherence timescales to a few tens of ns. Employing additional spectral filtering enhances contrast of Rabi oscillations by effectively selecting a single resonant atomic velocity class.

These results enable realization of different experimental protocols with warm atoms, which would previously necessitate laser cooling. Furthermore, we observe indications of the modification of the spontaneous emission rate due to the collective dipole-dipole interactions in our system, hinting at superradiant behavior in a dilute hot atomic medium.

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Aluminum monofluoride: three MOTs, and a laser-coolable molecule that can bounce off surfaces

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Until recently, direct laser cooling of molecules has been restricted to ‘open-shell’ species with $^2\Sigma$ electronic ground states. Aluminum monofluoride (AlF) is a closed-shell $^1\Sigma$ molecule and the first exception to this rule. AlF is among the most deeply bound and chemically stable diatomic molecules, with a binding energy of 6.9 eV, and exhibits a combination of properties that make it almost unique. Its two lowest electronic transitions (spin-allowed *and* spin-forbidden) are highly vibrationally diagonal, and feature rotationally closed Q -branches. Moreover, it can be conveniently produced in the gas phase via a thermochemical reaction driven at moderate temperatures (~ 900 K).

We have now loaded MOTs of AlF operating on the $A^1\Pi \leftarrow X^1\Sigma^+$ transition ($\lambda = 227.5$ nm), overcoming many of the challenges of deep ultraviolet light [1]. An interesting feature of AlF’s distinct electronic structure is that molecules can straightforwardly be laser-slowed and trapped in different rotational levels J ; we have so far shown that MOTs are effective for $J = 1, 2$ and 3. In addition, we have observed that, upon colliding with a room temperature surface, around a third of the molecules thermalise and leave the surface again. This opens the possibility to load molecular MOTs from warmer sources than the cryogenic setups used at present. In this talk, I will give a status update on our experiments in Berlin, efforts to laser cool and trap more highly excited rotational levels, and how we might leverage AlF’s narrow, spin-forbidden $a^3\Pi \leftarrow X^1\Sigma^+$ transition in future experiments.

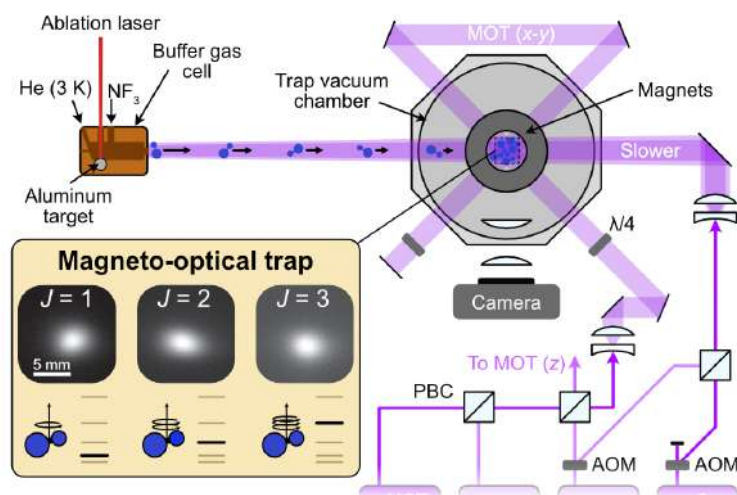


Figure 1: Experimental setup used to laser slow AlF molecules and load them into a magneto-optical trap. Fluorescence images of trapped molecules in rotational levels $J = 1, 2$ and 3 are shown in the box in the bottom left.

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Radiative Cooling Dynamics Governing PAH Survival in Astrophysical Environments

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The unexpectedly high abundance of small polycyclic aromatic hydrocarbons (PAHs) in cold molecular clouds is a topical puzzle in astrochemistry, with particular significance as JWST continues to reveal widespread infrared emission from PAH-like carriers across astrophysical environments. Using DESIREE, a specialised cryogenic electrostatic ion-storage ring providing “molecular cloud in a box” conditions ($T \approx 13$ K, $P \approx 10$ -14 mbar), we uncover the competition between unimolecular decomposition and radiative cooling processes in energized PAH ions. By following the spontaneous decomposition of stored ions over milliseconds to seconds and combining rate measurements with master-equation modelling that includes statistical dissociation, infrared emission, recurrent fluorescence, and isomerisation (if relevant), we identify the interplay between the mechanisms that govern the fate of isolated PAHs. Significantly, recurrent fluorescence, corresponding to radiative emission from thermally populated electronic states, plays a major role for small PAH cations with low-lying electronic states, thereby enhancing molecular survival on astrophysically relevant timescales. Our work suggests that efficient radiative stabilisation is not an exception but may be a general feature of small PAHs with suitable low-lying electronic structure, and that astrochemical models of PAH lifecycles should account explicitly for the combined action of recurrent fluorescence and infrared emission in radiative cooling. Ongoing work is exploring how the importance of infrared versus recurrent fluorescence in radiative cooling changes with PAH size.

Differential, single-photon interferometry with the ^{87}Sr clock transition for AION

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The AION project has built a tabletop prototype of a single-photon long-baseline atom interferometer using the ^{87}Sr clock transition [1]—a type of quantum sensor designed to search for dark matter and gravitational waves (Figure 1). Our prototype detector operates at the Standard Quantum Limit (SQL), producing a signal with no unexpected noise beyond atom shot noise. Importantly, the detector remains at the SQL even when additional laser phase noise is introduced, emulating conditions in a long-baseline detector such as AION or AEDGE where significant laser phase deviations will accumulate during long atom interrogation times. Our results mark a key milestone in extending atom interferometers to long baselines.

In this talk, I will outline the experimental steps we took towards this demonstration including the loading of two crossed optical dipole traps; velocity-slicing to select a subset of atoms with reduced temperature; injection of an artificial differential signal via the AC Stark shift; and analysis to assess the detector’s noise performance against a Monte Carlo model.

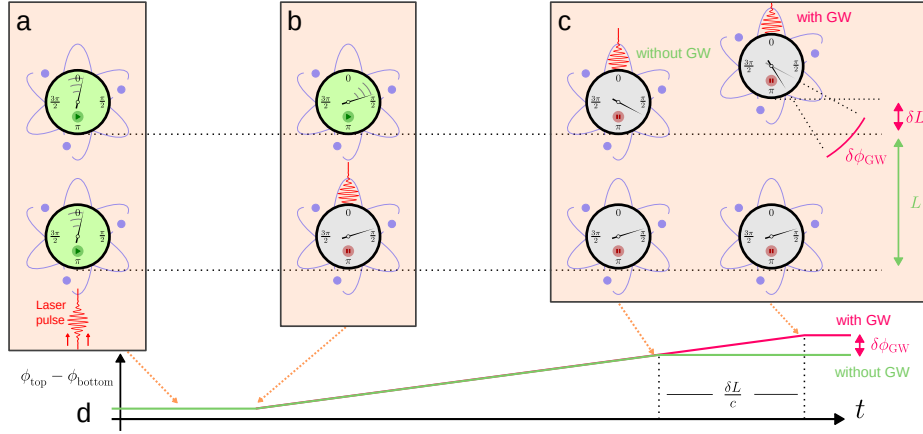


Figure 1: An illustration of the detector’s sensitivity to gravitational waves. In the moments before the final $\pi/2$ beam splitter pulse, the two atom interferometers can be treated as freely-falling atomic clocks (a) accruing phase at a rate ω_0 . The pulse halts this accrual of phase for the lower cloud, resulting in an accrual of differential phase (b, d) that continues until the pulse reaches the second cloud (c). In the proper frame of the bottom cloud (as pictured), the atoms are displaced by a transient gravitational wave. This has the effect of delaying (or hastening) this second interaction, imparting (at leading order) a detectable differential phase of $\Delta\phi_{\text{GW}} = \pm \frac{\delta L}{c} \omega_0$.

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Metastable level lifetime measurements and experimental transition rates in Fe II and Ti II for nebular diagnostics

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Singly ionized iron (Fe II) and titanium (Ti II) are some of the more common sources of spectra in astrophysical objects due to their high cosmic abundance and their richness in spectral lines. In the current work we present a novel technique and results to provide experimental radiative values for these important lines. The forbidden lines are crucial probes of physical conditions and elemental abundances, and this technique can be applied to a variety of elements.

Metastable levels are energy levels without allowed electric dipole (E1) decay transitions and their lifetimes are orders of magnitude longer compared to energy levels with E1-allowed decay transitions. For low-density astrophysical objects, where the average time between collisions is comparable to the lifetime of a metastable level, spectra emitted by the decay from those metastable levels can yield valuable information about their density distribution [1]. However, measuring lifetimes of metastable energy levels requires the time of flight for the probed ions to be comparable to the lifetime of the probed energy levels, so the experimental data on metastable energy level lifetimes is sparse.

In this work, lifetimes of several metastable energy levels in Fe II and Ti II have been experimentally measured for the first time by a Laser Probing Technique [3] at the DESIREE facility in Stockholm [2]. The metastable levels were populated by collisions in the ion source. Ions were injected and stored in the ring for a duration of several radiative lifetimes. The population of the metastable level (lifetime in ns range) was then probed, with a varying delay from the time of injection, by laser excitation to a higher-lying extremely short-lived (lifetime of few ns) state. The emitted higher-energy photons were recorded by a Photomultiplier tube (PMT). The lifetime was deduced from the exponential decay fit of the PMT signal (scaled by ion current) as a function of ion storage time.

The radiative transition rates (Einstein coefficients) crucial for nebular diagnostics can be derived if the lifetimes are combined with relative line intensities of the lines from a particular level. We use the nebular spectrum of Eta Carinae to derive these values.

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A new X-ray spectroscopy technique to probe the metastable fraction in an ECR ion source plasma

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Obtaining accurate measurements of cross sections for electronic processes (capture, ionization, excitation) in ion-ion/atom collisions crucially depends on the initial electronic states of the collision partners. The ion sources used for these collision experiments usually produce ion beams containing not only ground-state ions but also a variety of excited states. Although many of these species decay during the transport between the ion source and the collision chamber, the lifetime of some metastable species is long enough to allow them to reach the collision zone. Different schemes exist to extract the metastable fraction in an ion beam based on Auger spectroscopy techniques [1, 2].

Our setup at INSP is equipped with an ECR ion source delivering keV/u ion beams to a beamline ending in an experimental chamber. The ions travel a distance of 6 m (flight time of 3 μ s for 10 kV extraction). Our technique for measuring metastable fractions consists of recording the number of X-rays produced during the ion-atom collision as a function of the atomic pressure in the collision chamber. Under single-collision conditions, linear behavior is expected, with a non-zero intercept if metastable ions are present. Fig. 1 shows such an evolution in the case of collisions between Ar^{8+} and Ar atoms. Fig. 2 is an example of a X-ray spectrum exhibiting the $n = 3 \rightarrow n = 2$ transition at 250 eV. In this case, the metastable state involved is the $1s^2 2s^2 2p^5 3s^3 P$ state with a lifetime of 332 μ s. An ion fraction of this state of $5.3 \pm 1.5\%$ is deduced. Measurements with O^{6+} and Ne^{8+} , as well as the effect of source parameters on the metastable fraction, will also be presented at the conference.

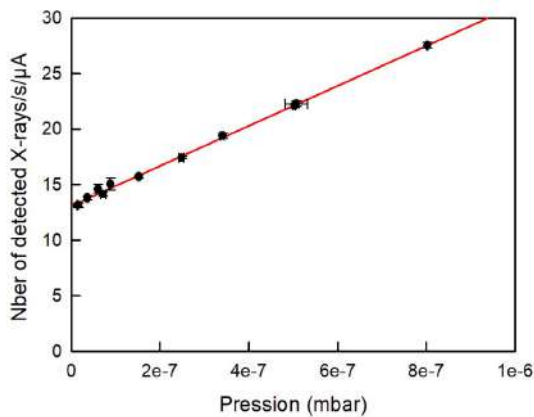


Figure 1: Normalized count rate vs. pressure in the collision chamber for an Ar^{8+} beam.

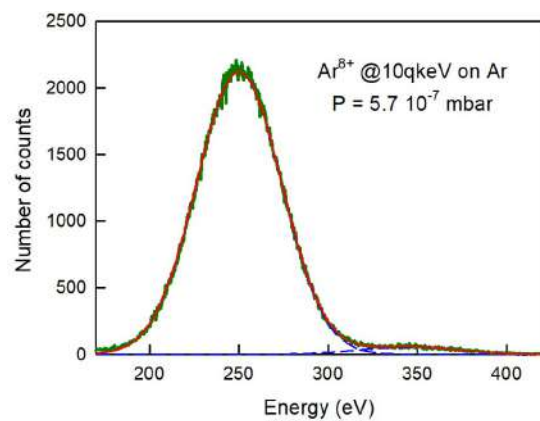


Figure 2: Spectrum of Ar^{8+} at 2 keV/u on Ar atoms with a pressure of 5.7×10^{-7} mbar.

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Time-Dependent Strong-Coupling Phenomena at XUV Wavelengths

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Recent advances in free-electron laser (FEL) technology have intensified interest in coherent light-matter interactions in the extreme ultraviolet (XUV) regime. Our group is working on theoretical models for this research field in close collaboration with experimentalists, c.f. Refs. [1,2]. The high intensity attainable with FEL pulses opens up previously inaccessible phenomena, such as *dressed-atom stabilization* [3,4], and the coherent nature of seeded FEL pulses enables ultrafast temporal control of strong coupling in atoms and ions resulting in rich dynamical absorption, photoelectron, and fluorescence spectra [5-7]. As the intensity is increased, the rotating wave approximation breaks down, and ultra-strong coupling effects on the attosecond timescale emerge [8].

In this talk, I will discuss how attosecond-phase control can be applied of femtosecond XUV-FEL pulse pairs to coherently control atoms in the strong-coupling regime. As an example, this allows us to control the manifestation of entanglement in photoionization because quantum correlations can be converted to classical correlations [6]. Further, I will discuss how such control can be used to reveal entanglement transfer from an electron-ion pair in photoionization to an electron-photon pair in fluorescence [7]. Theoretically, it is possible to follow the transfer process in the time domain and study how the *multipartite entanglement* between ion, electron, and photon develops and vanishes. We predict that pump-probe experiments can be used to control ionization from neutral atoms in intense XUV FEL fields by carefully controlling the attosecond phases of the fields to lock electron dynamics to stabilized dressed states on the Bloch sphere [3,4]. Conversely, we find that locking the electron to the other dressed state enhances photoionization [4]. The high intensity and high frequency of XUV FEL pulses allow us to study exotic nonlinear processes, *e.g.* ultrafast two-photon Rabi oscillations [8] and *giant counter-rotating oscillations* on the attosecond timescale [8]. Overall, our calculations of time-dependent dynamics in composite electron-ion-photon systems pave the way for studies of time-resolved entanglement and coherent control in more complex systems in the future.

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Matter-wave interferometry of metal nanoparticles as a platform for fundamental and metrological insight

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Throughout the course of the last century, the quantum superposition principle has evolved into a core concept in modern physics. Yet, it remains unclear whether center-of-mass spatial superpositions can continuously be observed as the mass of physical systems approaches those of our macroscopic world, or if there is a fundamental limit at which the validity of the Schrödinger equation breaks down. Here, we introduce the MUSCLE interferometer - a near-field Talbot-Lau interferometer equipped with three UV optical gratings - as a tool to answer these questions in the nanometer-sized regime. We demonstrate quantum interference of sodium nanoparticles with masses greater than 170,000 Da, making it evident that nanometer-sized objects can be delocalized over distances exceeding their size by an order of magnitude [1]. The quantum macroscopicity [2] of $\mu = 15.5$ obtained for this result establishes matter-wave interferometry as a strong candidate to test a variety of macrorealist modifications to the Schrödinger equation. Moreover, we show that the fringe stability and displacement resolution achieved by this experimental platform makes it suitable for deflection-based metrology in a wide range of masses [3].

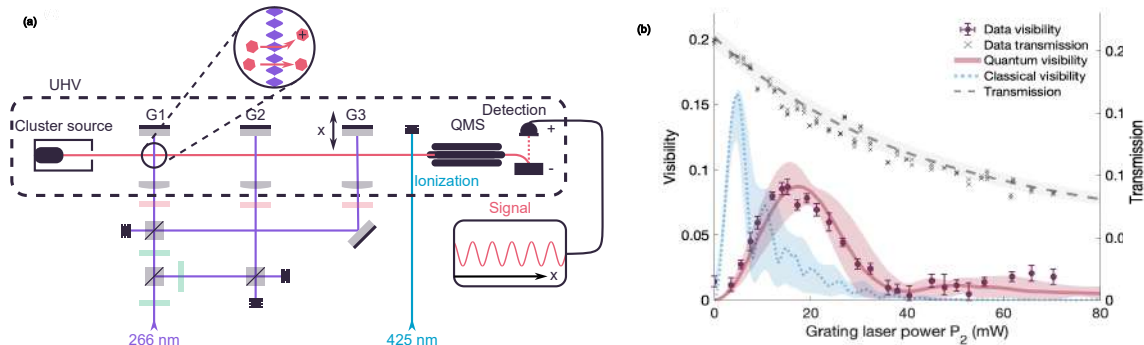


Figure 1: **(a)** Schematic of the MUSCLE interferometer. **(b)** Interference fringe visibility versus grating laser power for sodium clusters with a mean mass of 172,000 Da.

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High-Precision Spectroscopy of Single Molecular Hydrogen Ions at ALPHATRAP

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Diatomic molecular hydrogen ions (MHI) are the simplest molecules and thus ideal systems for testing QED and fundamental physics through comparison of high-precision measurements with theoretical predictions [1]. At the ALPHATRAP Penning-trap apparatus located at the MPIK we measured the bound electron g -factor of HD^+ in the rovibrational ground state [2]. This result can be compared to most recent *ab initio* theory, which includes relativistic and QED corrections up to order α^5 [3], and shows excellent agreement with our measurement at a relative precision level of 0.20 ppb. In addition, the scalar spin interaction coefficients E_4 and E_5 were extracted with 44 ppb and 151 ppb relative uncertainty [2]. These results can also be compared to recent hyperfine theory (HFS) [4] and we observe moderate 1.9σ and 3.1σ tensions, respectively.

Rovibrational laser spectroscopy on MHI enables high precision determinations of fundamental constants like the proton-to-electron mass ratio. Additionally, these measurements allow us to test QED as well as HFS theory in a wide range of rovibrational levels [5]. In a next step, we carried out high-precision laser spectroscopy of the $(v, N) = (0, 0) \rightarrow (5, 1)$ transition in HD^+ . We have measured several hyperfine components of this transition to sub-ppt statistical precision, which we can then compare to high-precision theoretical calculations.

I will summarize the results from this measurement campaign and provide an outlook for future measurements. In particular, I will discuss how our Penning-traps can serve as a versatile platform for ultra-high precision laser spectroscopy - particularly of molecular hydrogen ions, including H_2^+ and its antimatter equivalent $\bar{\text{H}}_2^-$ [6].

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Cavity-enhanced spectroscopy in the deep cryogenic regime for quantum sensing and metrology

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High-finesse cavity-enhanced spectrometers play a crucial role in both fundamental research and practical applications. Lowering the system's operating temperature from room temperature to the deep-cryogenic regime provides substantial advantages for spectral measurements, such as narrowing the Boltzmann distribution of rotational states, suppressing Doppler broadening, enhancing peak absorption and freezing out unwanted molecular species. We present the first cavity-enhanced spectrometer designed to operate entirely within the deep-cryogenic regime, reaching temperatures as low as 4 K [1] (Fig.1). In our system, the entire optical cavity, including the mirrors and piezo actuator stack, is cooled uniformly along with the gas sample, ensuring that the sample stays in thermodynamic equilibrium [2]. With it we performed a Doppler-limited spectroscopy of the S(0) (1-0) rovibrational transition in molecular hydrogen, reaching unmatched agreement with the latest theoretical prediction within its stated uncertainty. This level of consistency probes molecular quantum theory at the tenth significant digit and, to the best of our knowledge, provides the most precise validation of quantum electrodynamics in a four-body system to date [3].

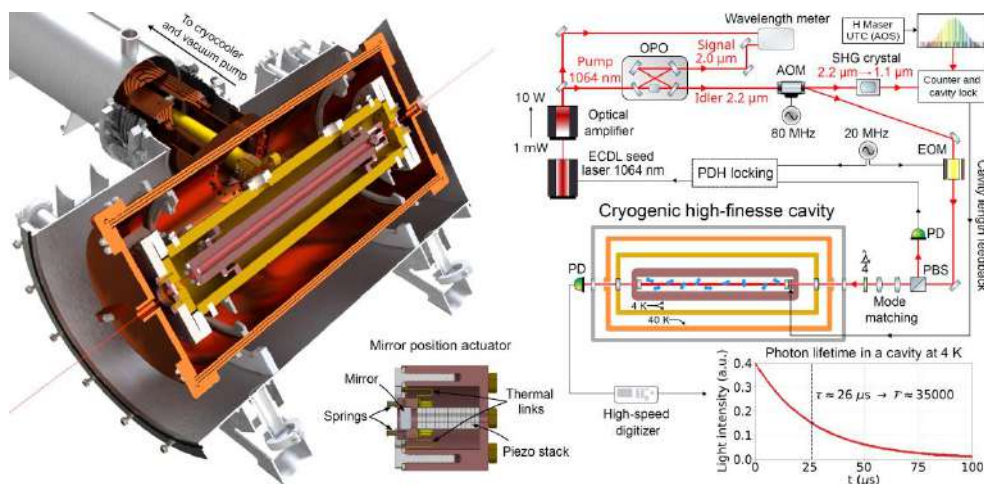


Figure 1: Spectrometer based on a cryogenic high-finesse cavity. (left panel) Illustration of the cryogenic part. (right panel) Simplified scheme of the experimental setup.

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Structuring atomic interactions with topological light

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We can shape and twist the structure of light, generating phase and polarisation vortices within the 3D electromagnetic vector field. Atoms are ideal in sensing and responding to such light via their dipole interaction. I will introduce methods for the generation and analysis of vector light beams and present two approaches to test vectorial light matter interaction – atomic state interferometry and spin selective spectroscopy of atomic vapours.

With atomic state interferometer, we can imprint optical polarisation textures onto atomic spin structures in cold rubidium vapours at some 100uK, with promising applications in magnetometry and quantum sensing [1, 2]. More recently we have used the characteristic frequency response of circular birefringence and dichroism of an optically pumped rubidium vapour to generate spatio-spectral vector light, correlated in its frequency, polarisation and spatial degrees of freedom.

Polarization selective measurements then allows us to perform spatially resolved polarization spectroscopy. We demonstrate the translation of frequency shifts into an image rotation, observing on resonance a rotation in the order of 98 mrad per MHz [3].

We expect that the interaction of atoms with topological light may find applications in high-precision spectroscopy, magnetometry, quantum gyros and the nature of topological effects.

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Non-Markovian dynamics and bound state generation in waveguide QED

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Waveguide QED describes the dynamics of quantum emitter arrays coupled to an electromagnetic field that propagates in one dimension. In different parameter regimes, the theory can be successfully applied to analyze both the coupling of natural atoms or molecules to optical waveguides and the interaction of artificial atoms in the microwave domain. One of the outstanding features of the theory is the existence of bound states in the continuum (BICs), where, under specific resonance conditions, the emitter excitations combine into stable configurations, often featuring interesting entanglement patterns. However, the tendency of BICs to decouple from propagating also makes their generation non-trivial.

In this talk, we will discuss two cases in which a rather unexpected help to BIC generation comes from delay-induced non-Markovian effects, which occur when the timescale of photon propagation across the array of emitter becomes comparable to their lifetime. First, we will show how a protocol of single-photon scattering on a pair of two-level emitters, combined with a properly engineered time variation of the qubit detuning, represents a feasible strategy of BIC generation, whose effectiveness increases with the photon propagation delay. Then, we shall consider the dynamics of an array of initially excited two-level emitters coupled, where superradiance is expected in the Born-Markov approximation. In the presence of delay-induced non-Markovianity, the superradiant burst breaks into a structured train of correlated photons. Moreover, the asymptotic state of the system features emitter–photon and emitter–emitter entanglement, due to relaxation on BICs, which is suppressed in the Markovian limit. We conclude by discussing ongoing development of strategies to increase the entanglement between the emitters by manipulating the BICs generated in the process.

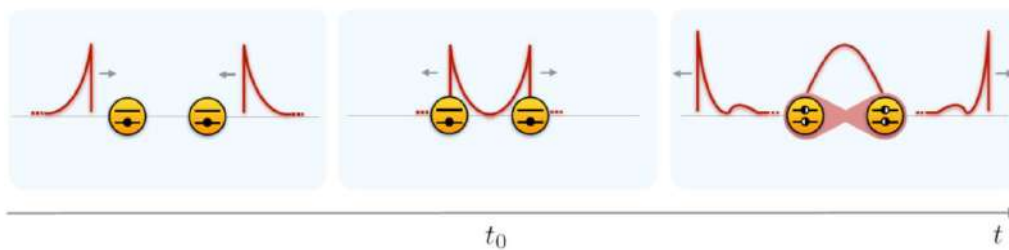


Figure 1: Schematics of BIC generation of a qubit pair via scattering of a single parity-invariant photon. The effective coupling between emitters and photons is turned on at time t_0 .

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Relativistic reason for quantum probability amplitudes

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Optical frequency comb spectroscopy at low temperatures for laboratory astrophysics applications

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Laboratory spectroscopy is essential for the interpretation of modern astrophysical observations, which increasingly probe cold and dilute environments where molecules exhibit narrow spectral features and non-thermal population distributions. While optical frequency comb spectroscopy has become a powerful tool for precision measurements, its application has so far been largely limited to stable and near-equilibrium systems.

In this invited talk, I will present recent advances extending frequency comb spectroscopy to low-temperature and non-equilibrium environments relevant to laboratory astrophysics. The central development is the implementation of comb-based Fourier transform spectroscopy with sub-nominal resolution [1-2] in supersonic jet expansions, cold plasmas, and, more generally, reactive media at low temperature.

In a first step, we demonstrate comb-based spectroscopy in a supersonic jet [3], providing access to cold, isolated molecules under well-defined conditions. The combination of cavity enhancement and Fourier transform detection enables broadband, high-resolution measurements with intrinsic frequency calibration. A self-referenced scheme allows direct sampling of comb modes, improving robustness and enabling accurate retrieval of rovibrational line parameters in cold conditions.

We also extended this approach to non-equilibrium environments such as pulsed plasmas, where transient species and evolving rovibrational populations can be probed. By introducing time-resolved frequency comb Fourier transform spectroscopy [4], it becomes possible to follow the dynamics of molecular systems with both spectral and temporal resolution. These developments pave the way toward the quantitative study of reactive processes at low temperature with state-resolved information.

This work establishes frequency comb spectroscopy as a versatile tool not only for precision measurements, but also for the investigation of cold and reactive environments. It opens new perspectives for laboratory astrophysics, from the production of accurate spectroscopic data under astrophysically relevant conditions to the experimental study of reaction dynamics in cold media.

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Metrology of gas temperature and amount of substance using high-resolution molecular spectroscopy

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The redefinition of the SI introduced a fixed value of the Boltzmann constant, establishing a direct relationship between temperature and thermal energy (kT) and opening the way for new primary thermometry techniques. Two optical spectroscopic methods have emerged as particularly promising: Doppler broadening thermometry (DBT) and line-ratio thermometry (LRT) based on rovibrational molecular transitions. Both approaches have recently demonstrated temperature measurements with uncertainties at the millikelvin level near ambient T . DBT currently provides the highest accuracy at very low gas pressures, whereas LRT remains effective across a much wider pressure range, making it attractive for a broad set of applications.

In this work, we present temperature measurements obtained using LRT in the CO (3–0) vibrational band. The measurements are performed with cavity mode-dispersion spectroscopy (CMDS) [1,2], where both axes of molecular spectrum are determined from the resonance frequencies of a high-finesse optical cavity, providing direct traceability to a primary frequency standard. By combining the LRT approach with state-of-the-art *ab initio* line intensities [3], we obtain a temperature uncertainty below 20 mK at 296 K [4]. In addition, the use of accurate absolute line intensities together with spectroscopic temperature determination enables fully optical gas concentration measurements with precision at the permille level over a pressure range extending from 50 Pa to 20 kPa.

This methodology expands the operating pressure range of high-accuracy spectroscopic thermometry by more than an order of magnitude compared with previous techniques, while also providing a fully optical, non-invasive, and species-selective route to primary amount-of-substance measurements. We further examine the present limitations of the method and discuss opportunities for improving both spectroscopic modeling [5] and reference molecular data [6,7], which are essential for advancing the accuracy of primary thermometry and concentration measurements.

The research was supported by the state budget of Poland, allocated by the Minister of Education and Science under the "Polska Metrologia II" program, project no. PM-II/SP/0011/2024/02, and the European Partnership on Metrology project "22IEM03 PriSpecTemp".

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Laser cooling of positronium with broadband laser pulses: towards intense, cryogenic Ps clouds

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Doppler laser cooling of positronium (Ps) – the short-lived bound state of an electron and a positron – was proposed more than 30 years ago along the 1^3S – 2^3P transition as a key route to surpass current limits in the production of cold Ps samples and to broaden the scope of precision experiments based on this purely leptonic atomic system, ranging from bound-state QED tests to the search for new physics in the lepton sector and to gravitational tests of the Weak Equivalence Principle (WEP) with antimatter.

The first experimental demonstration of Ps Doppler cooling with a broadband laser pulse [1], carried out by the AEgIS (Antimatter Experiment, Gravity, Interferometry, and Spectroscopy) collaboration at CERN's Antimatter Factory, validated this long-standing proposal. The experiment employed a custom-designed broadband alexandrite laser system [2] operating in the deep saturation regime of the 1^3S – 2^3P transition. The laser, specifically developed for this application, delivers mJ-level pulses in the deep UV (243 nm) over a useful cooling bandwidth of about 360 GHz, with pulse durations exceeding 100 ns and a rapid falling edge. Cooling was diagnosed by measuring the Doppler broadening of the 1^3S – 3^3P line with a second, independent narrow-band laser immediately after the cooling pulse. The equivalent transverse temperature of the Ps atoms emerging from a porous silica target at room temperature dropped from 380 K to 170 K, corresponding to a reduction of the rms transverse velocity from 54 km/s to 37 km/s (figure 1).

In this talk I will review the physics and experimental implementation of this first demonstration, and discuss recent developments aimed at extending the technique towards sub-100 K Ps sources, longer interaction times, and operation in the strong magnetic fields required by antihydrogen production schemes [3]. The resulting cold and bright Ps sources open new prospects for precision spectroscopy of positronium, pulsed antihydrogen beam formation, and WEP tests with leptonic antimatter.

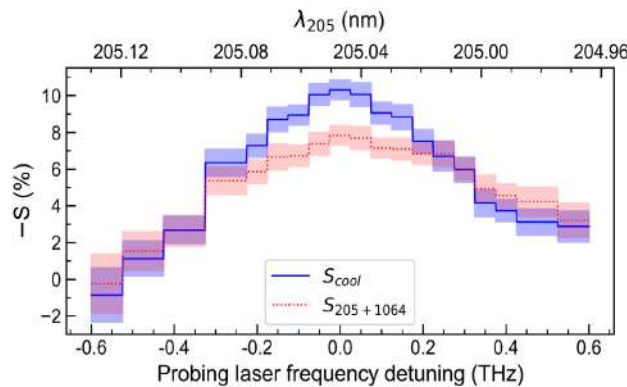


Figure 1: Narrowing of the 1^3S – 3^3P line of Ps after laser cooling is applied. Adapted from [1].

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EGAS 57

Monday Poster Session

Monday, June 22nd 16:30-18:30

Towards a tabletop storage ring for visualizing charged-particle motion

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Models and analogies are essential in physics education when students are introduced to phenomena that are difficult or impossible to observe directly [1]. In atomic and molecular physics, storage rings play a central role in experimental research, but their enclosed vacuum chambers make the underlying beam dynamics difficult to visualize in educational settings. This project therefore aims to develop a tabletop storage ring that can be used as an educational tool, allowing students to observe and control an electron beam. The tabletop storage ring will be a geometric replica of one of the electrostatic storage rings used at DESIREE in Stockholm [2]. It will be constructed with a transparent chamber filled with a fluorescent gas, making the electron beam visible, similar to the electron *ronde* built by the Sciences ACO association [3]. Electric fields will be used to control the motion of charged particles.

The first stages of this project will be presented, where the construction of a linear electron accelerator, inspired by a Crookes tube, serves as the first step towards the tabletop storage ring. The fluorescent gas used in the chamber of the linear electron accelerator will be investigated in order to optimize the visibility and intensity of the electron beam.

The tabletop storage ring, featuring a visible and controllable electron beam, can be used for a variety of educational purposes, including outreach activities, student laboratory exercises involving the motion of charged particles in electric fields, and demonstrations in atomic physics where spectral lines can be studied. By providing a hands-on visualization of charged particles moving in electric fields, the setup can help students connect abstract field concepts to observable beam motion. As a model inspired by real research equipment, it may also support students' understanding of how advanced experimental instruments operate.

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Series of doubly excited states converging to the double-ionization threshold of Strontium atoms

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Atoms in highly doubly excited states (approximate principal quantum numbers of the inner and outer Rydberg electrons N and $n \gg 1$) are fascinating objects at the center of many physical phenomena such as electronic resonances, chaos and non-trivial correlation effects [1,2]. Photo-excitation spectra of alkaline-earth atoms (Mg, Ca, Sr, Ba) serve as probes to study electronic correlation in highly doubly excited states. We focus here on Sr atoms and theoretically analyze a spectrum recorded at the Max Born Institute. The experiment consists of photoexciting Sr atoms prepared in the $6d19l$ ($l \sim 15$) state to doubly excited states before converting the excited population to Sr^{++} ions via a combination of photo- and field-ionization [3]. Our goal is to explain the origin of a series of lines (figure 1) appearing right above hydrogenic single-ionization thresholds and, remarkably, converging up to the double-ionization (DI) threshold.

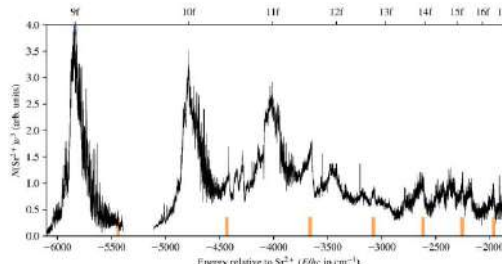


Figure 1. Experimental photoexcitation spectrum [2]. The vertical axis shows the number of Sr^{++} ions scaled by the cube of the wavenumber relative to the DI. The horizontal axis shows the wavenumber of the excitation laser relative to the DI threshold. The lines under consideration are marked by orange bars.

As we are only 0.5 eV below the DI threshold, the density of states is very large, and many eigenstates must be computed for an accurate reproduction of the spectrum. This requires diagonalizing large parts of the Hamiltonian via ab-initio configuration-interaction computations (e.g. $N=7, \dots, 10$ and $n \rightarrow 100$) [2,3]. Using large-scale parallelization techniques, we can reproduce photo-excitation spectra for unprecedentedly high excitation energies. Our results are validated by direct comparison with the experimental spectrum, yielding good agreement. Theory reveals that only a handful of short-lived ($\tau = 0.1$ ps) resonances fairly reproduce the spectrum right over the orange bars. The inner electron shows an important s or d character, while the outer, highly excited electron departs significantly from conventional Rydberg wavefunctions. A careful analysis of the interactions responsible for these resonances and their marked appearance in the experimental spectra is under way.

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Magnetic shielding in the atomic hydrogen anion

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The hydrogen anion H^- is the lightest stable anion and its bound state and resonances are well studied, but magnetic shielding has not been computed to comparable accuracy. Due to the planned comparison of the bare antiproton to H^- in a Penning trap with extremely high precision, we study the magnetic shielding of H^- using nonrelativistic quantum electrodynamics theory (NRQED). Within NRQED the shielding constant for a light atomic system admits a double expansion in α

$$\sigma = \alpha^2 \sigma^{(2)} + \alpha^4 \sigma^{(4)} + \alpha^5 \sigma^{(5)} + \dots$$

and the electron-to-nucleus mass ratio m/M

$$\sigma^{(n)} = \sigma^{(n,0)} + \frac{m}{M} \sigma^{(n,1)} + \left(\frac{m}{M}\right)^2 \sigma^{(n,2)} + \dots$$

We compute the nonrelativistic shielding (of order α^2), as well as finite nuclear mass ($\mathcal{O}(m/M)$), relativistic (α^4), and partial QED (α^5) corrections and give estimates of the higher-order terms.

We find that the finite nuclear mass correction is the most significant one to shielding in H^- , more than twice as large as the relativistic correction. Our final result for the shielding constant has nine-parts-per-trillion accuracy and paves the way for a direct antiproton-to-proton magnetic moment comparison by the BASE Collaboration [1, 2].

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Zeeman hyperfine structure of atomic lutetium by laser spectroscopy investigations

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Lutetium is the last element of the lanthanide group. Despite its relatively low magnetic moment (only $3\mu_B$) in comparison to the other lanthanides, owing to its closed 4f shell, both neutral lutetium (Lu I) and singly ionized lutetium (Lu II) have found applications in quantum engineering, for example, as frequency standards, and in fundamental physics, for instance, in studies of the temporal evolution of atomic quantum states, underscoring their relevance in quantum materials research.

We present preliminary results of Landé g_J factor measurements for 15 electronic levels of the lutetium atom. The measurements were performed by observing the Zeeman effect on the hyperfine structure using laser spectroscopy in a hollow-cathode discharge lamp placed in a constant magnetic field, with laser-induced fluorescence detection. In total, 34 spectral lines were recorded, allowing us to determine five new g_J values. The remaining 10 values were refined with substantially improved precision compared with earlier measurements. In addition, the results enabled us to assess the accuracy of our semi-empirical analysis of the fine structure of Lu I reported last year [1, 2].

The results were obtained using a new proprietary program with a graphical user interface that allows interactive adjustment of theoretical model parameters, graphical visualization of the results, and automatic fitting of the theoretical curve to experimental data. To ensure high performance, the program uses CPU multithreading and the Gpufit library, which significantly reduces the time required for the calculations.

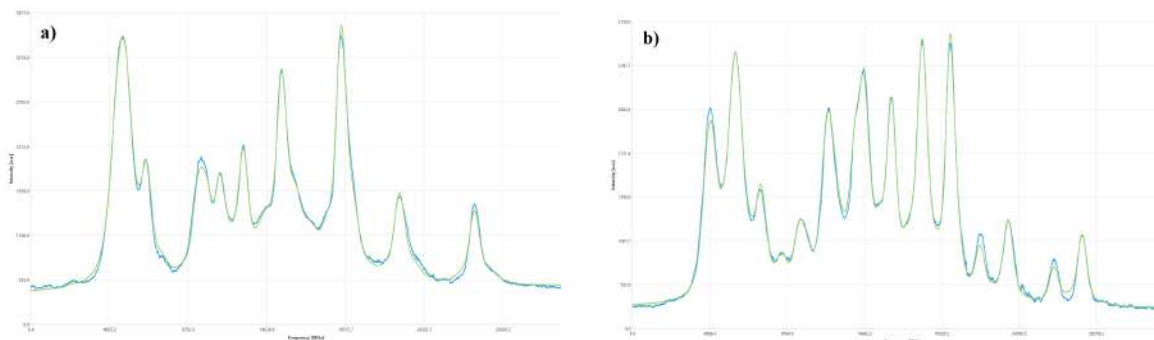


Figure 1: Recorded Zeeman- hfs patterns of the spectral line $\lambda = 634.534$ nm in the lutetium atom (blue line) along with the least-squares fitted curves (green line) a) for the polarization π b) for the polarization σ .

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Analysis of the luminescence properties of $\text{Pr}^{3+}:\text{YAG}$ within the framework of an extended Judd-Ofelt theory

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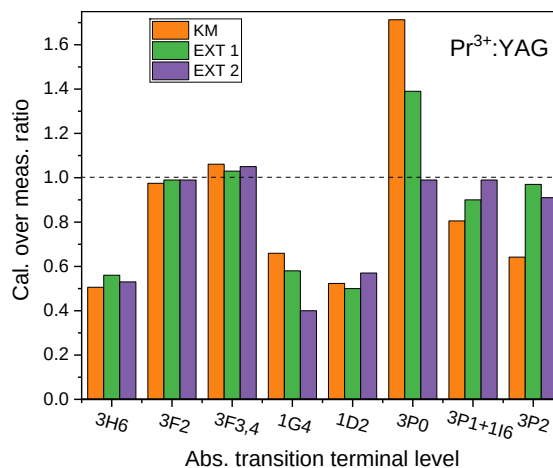
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Radiative transitions in rare-earth-doped crystals play a central role in lasers and optical-fiber telecommunications. In a joint theoretical and experimental study, we revisit the luminescent properties of two Pr^{3+} -doped materials, using a recently developed extension [1] of the well-established Judd-Ofelt theory. Based on accurate properties of the rare-earth dopant, this model allows for relaxing some strong selection rules and approximations of the standard theory and its earlier extensions [2]. Our model also better accounts for the influence of the 4f5d excited electronic configuration, crucial in 4f-4f transitions inside solids. We show that it improves the agreement between calculated and measured absorption oscillator strengths in $\text{Pr}^{3+}:\text{YAG}$, especially for high-energy transitions, which are more influenced by the 4f5d configuration (see Figure 1). The model can also predict accurate fluorescence lifetimes and branching ratios. Based on those results, we discuss new potential laser transitions in the visible or near infrared ranges with $\text{Pr}^{3+}:\text{YAG}$.

Figure 1: Ratio between calculated and experimentally measured oscillator strengths obtained with different models: “KM” is the modified Judd-Ofelt theory by Kornienko *et al*, [2]; “EXT. 1” and “EXT. 2” are two versions of our own extension [1]. In the x axis, the transitions are labeled with their upper levels, and are sorted in increasing order of energy. The lower level is always the ground one $[\text{Xe}]4f^2\ ^3\text{H}_4$



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Decaying Feshbach resonances in ultracold Er + Li and Dy + K

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Highly magnetic atoms have multiple applications in modern day physics, including quantum simulations, computing or high-precision spectroscopy. Thanks to their rich energy level structure and multitude of couplings they show an extremely dense pattern of bound states. One of the most important way of controlling their interactions and scattering properties are Feshbach resonances, in which the closed channels of colliding species are coupled to the continuum of scattering states. This study shows that ultracold Er+Li and Dy + K are great candidates for analysis. An approach using the coupled-channel method is used to numerically solve the Schrodinger equation and obtain scattering results. The resonance spectra give insight into the system's nature, proving that their resonances are tunable and controllable.

Feasibility studies of laser cooling in the cobalt atom

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The studies of cobalt content in stars and supernovae can provide valuable information regarding stellar evolution. Since the only stable isotope (^{59}Co) is bosonic, it can also be considered a possible candidate for Bose-Einstein condensation. This provides strong motivation to search for cooling schemes to enable reducing the temperature, ultimately to the required range. The first step can be done with laser cooling. This, however, can be challenging, since there are no cycling transitions in the cobalt spectrum and there are many expected decay channels from the upper levels of the possible cooling transitions. Nevertheless, cobalt has a relatively strong magnetic moment, which makes cooling more plausible with methods analogous to those developed for elements with open f shell, such as erbium [1], dysprosium [2], thulium [3] and holmium [4], which were successfully cooled in magneto-optical traps (MOTs).

Semi-empirical calculations regarding the probabilities of all relevant transitions in atomic cobalt [5] indicated that decays from the upper levels of the possible cooling transitions to a certain metastable level are particularly strong. Therefore, instead of single cooling transitions $J = 9/2 \rightarrow J' = 11/2$, Λ cooling systems are considered.

The main aim of the research is to measure the hyperfine structure (*hfs*) of selected spectral lines (mainly from the levels proposed as the upper levels in the Λ cooling schemes) to enhance the precision of *hfs* constants. This, in turn, will allow more reliable semi-empirical predictions regarding the probabilities of the leaking transitions. The transitions involved directly in the considered Λ cooling schemes lie in the UV, so direct measurements in our lab are not possible.

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Single-beam grating-chip 3D and 1D optical lattices

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Ultracold atoms are crucial for unlocking truly precise and accurate quantum metrology and provide an essential platform for quantum computing, communication, and memories. One of the largest ongoing challenges is the miniaturization of these quantum devices. Here, we show that the typically macroscopic optical lattice architecture at the heart of many ultraprecise quantum technologies can be realized with a single-input laser beam on the same diffractive chip already used to create the ultracold atoms. Moreover, this inherently ultrastable platform enables access to a plethora of new lattice dimensionalities and geometries, ideally suited for the design of high-accuracy, portable quantum devices [1].

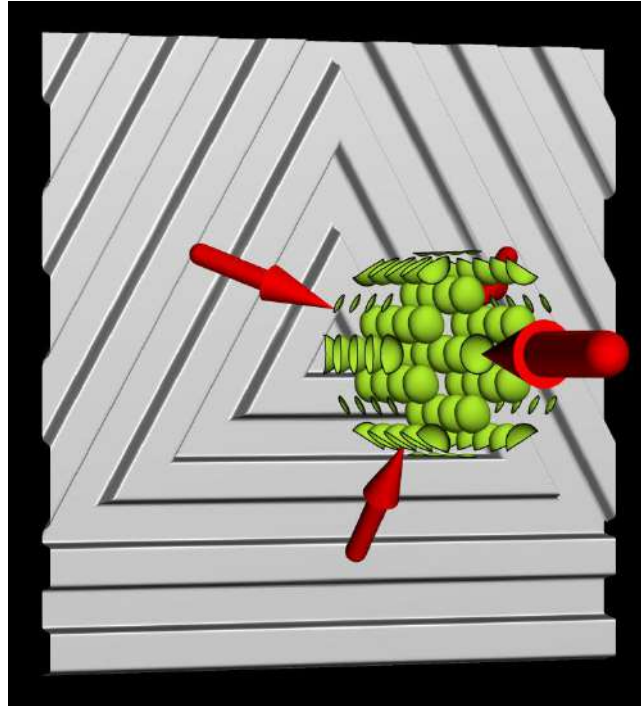


Figure 1: A triangular diffraction grating, when illuminated by a single laser beam (large arrow), creates diffracted orders (thin arrows) with stable phases locked to the grating surface. Here we illustrate the 3D optical lattice generated by the four combined laser beams, but 1D and 2D lattice geometries can be created with the same microfabricated grating chip.

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Practical primary thermometry via Doppler broadening

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Doppler-broadening thermometry (DBT) can be used as a calibration-free primary reference suitable for practical applications, e.g. reliably measuring temperatures over long periods of time in environments where sensor retrieval for recalibration is impractical. We report on our proof-of-concept investigations into DBT with alkali metal vapour cells, with a particular focus on both absorption and frequency accuracy during scans. We reach sub-kelvin temperature accuracy, and experimental absorption fit residuals below 0.05 %, in a simple setup [1]. The outlook for portable, practical devices is bright, with clear prospects for future improvement.

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Isotopic mass effects on collisional parameters in a dual-species atomic clock

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We investigate the isotopic dependence of collisional broadening and frequency shifts of the Hg clock transition $^1S_0$ - $^3P_0$, induced by collisions with Rb atoms, across a temperature range from 1 nK to 1 K. To this end, the Born-Oppenheimer effective interaction potential is modeled by incorporating the leading long-range van der Waals coefficients. For elastic collisions, we analyze how the collisional line-shape parameters depend on the reduced mass of the interacting particles, as well as on the variation of the scattering lengths in both the ground and excited states of the Hg-Rb system in the microkelvin regime. Full quantum scattering calculations are compared with a semiclassical approximation for evaluating collisional widths and shifts. Our results demonstrate that shape resonances in both ground and excited scattering channels lead to pronounced variations in collisional line-shape parameters as the reduced mass of the colliding atoms changes. Additionally, we studied the role of inelastic collisions, which may induce universal behavior and significantly influence the dependence of collisional broadening and frequency shifts on the isotopic combination of colliding atoms. This study provides insights to ongoing experiments focused on the collisional processes in a trapped ultra-cold mixtures of Hg and Rb atoms [1].

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Computational study for the bound states of ^{171}Yb - ^{174}Yb molecular system

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Recently, a hybrid system consisting of a dual-isotopic ytterbium (Yb) array has been realized, where the nuclear spin qubit of fermionic ^{171}Yb serves as a data qubit and bosonic ^{174}Yb acts as an ancilla qubit, enabling nondestructive, state-selective qubit readout [1]. Such a hybrid system offers significant potential for implementing ancilla-based quantum error correction protocols. To guide experiments on molecular formation, we developed a multichannel interaction model for the fermion-boson heteronuclear Yb_2 system in the molecular excited state dissociating into the $^1\text{S}_0$ and $^3\text{P}_1$ atomic asymptotes. Our model extends prior approaches for heteronuclear bosonic systems [2] by incorporating the nuclear spin of the fermionic Yb, following Ref. [3]. Using the Born-Oppenheimer effective interaction potential with leading long-range van der Waals terms, we numerically solved the Schrödinger equation via the mapped discrete variable representation (DVR) method [4] to compute the ro-vibrational bound states. The calculated bound state energies are in good agreement with previous theoretical predictions and experimental results [1], demonstrating the reliability of our model for guiding future studies of dual-Yb atom arrays and their applications in quantum information processing.

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Proposal for Production of Ca Heavy-Rydberg States by Electron Transfer From Ultra-Long-Range Rydberg Molecules

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Heavy-Rydberg (HR) ion-pair states are molecular states composed of a positive and a negative ion that interact Coulombically. Their vibrational wavefunctions and energies thus behave similarly to those of electronic states in the Hydrogen atom. In the $\text{Ca}^+(4s)\text{-Ca}^-(4p_i)$ case, because of the very small Ca electron affinity, the Coulomb potential of heavy-Rydberg states crosses the molecular potential energy curves of many ultra-long-range Rydberg molecules (ULRRM). These molecules result from the multiple scatterings of a Rydberg electron off a neutral perturbing atom [1]. Their bond length is similar to the size of the Rydberg atom, and ranges from ~ 200 to ~ 450 a_0 for the principal quantum number $n=10\text{-}15$ of the Rydberg electron considered in this work. Their potential energy curves indeed cross the HR Coulomb one in a region where the electronic wavefunctions of the two molecular systems significantly overlap, yielding a non-vanishing electron-transfer-type interaction between them.

Exciting a HR state directly from a ground-state molecule is a very unlikely process due to the poor overlap between the vibrational wavefunctions of the two systems and has only been achieved via multi-photon excitation schemes. We suggest and theoretically demonstrate that the interaction between ULRRM and HR potential energy curves in Ca is of great interest, as it results in significant mixing between the two systems and consequently enables direct excitation of cold HR ion pairs via excitation of the ULRRM component of the mixed vibrational states. This excitation scheme, besides leading to the formation of cold HR molecules, could be of great interest to study controlled electron transfer.

To investigate this proposal, we first determine the potential energy curves of the ULRRM by using the Fermi-Omont pseudopotential [2]. The electronic interaction between the two molecular systems is then calculated both numerically and analytically [3], employing the generalized local-frame transformation [4]. We then solve the Schrödinger equation by means of a discrete-variable-representation method with exterior complex scaling, enabling us to treat the dissociation channels and to find the vibrational wavefunctions, states, and lifetimes, following a non-adiabatic description of the electron-transfer interaction. Finally, excitation efficiencies and lifetimes are discussed. Preliminary results show that HR states can efficiently mix with ULRRM for n values between 10 and 13 and that this mixing substantially increases their direct excitation probability from a cold atomic gas, reaching values comparable to the pure ULRRM states. Ongoing calculations are considering other excitation schemes, relying on multi-step processes to increase the efficiency and range of n values that could be used to prepare HR states.

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Overcoming capture limitations in grating magneto-optical traps with a 2D MOT

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Grating magneto-optical traps (gMOTs) are an attractive route to compact laser-cooling architectures, but loading them from cold atomic beams is not straightforward. In contrast to a conventional six-beam MOT, atoms approaching a gMOT experience incomplete beam geometries and radiation pressure from outwardly diffracted light before reaching the trapping region. As a result, radial loading with a cold atomic beam requires tight control of the atomic trajectory and velocity distribution.

Here we investigate this capture limitation for a gMOT loaded from a 2D MOT source [1]. Using a simple average-force model, we show that outwardly diffracted beams produce transverse deflections that restrict the phase-space acceptance for radial loading, effectively imposing a minimum capture velocity in addition to a maximum capture velocity for a gMOT. We then show that these limitations can be largely avoided by loading axially through a central aperture in the grating, providing direct access to the trapping region.

Experimentally, we implement axial loading using a 2D+ MOT and observe loading rates of 2×10^9 atoms s^{-1} . These results identify a geometric constraint on capture in beam-loaded grating MOTs and show that efficient loading requires matching the source to the trap acceptance. This work enables high-flux cold-atom sources in compact, optically accessible geometries.

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Magnetic trapping and non-destructive microwave detection of cold atoms on an atom chip

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In this work, we investigate the manipulation and detection of ultracold ^{87}Rb atoms using an atom chip platform. A magnetic trap is realized using a Z-shaped current-carrying wire in combination with an external bias magnetic field, forming a highly controllable trapping potential near the chip surface. By finely tuning the external bias field, we achieve precise displacement of the trapped atom cloud, enabling its accurate positioning on the chip. In addition, we study the non-destructive interaction between microwave fields and hyperfine ground states of atoms [1]. The goal being the improvement of the signal-to-noise ratio of our non-destructive detection method. This solution is aimed at reducing dead time between sensor's interrogation sequences [2]. Its working principle is based on the measurement of the radiation resistance of a microwave signal under the influence of a cold atomic ensemble. The atoms are illuminated by a horn antenna under off-resonant conditions with respect to the clock hyperfine transition. This approach enables probing of the atomic population difference while preserving the system quantum coherence. Thus, our work provides a foundation for the development of compact and lightweight cold-atom platforms for miniaturized inertial navigation systems [3].

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Observation of Scattering Resonances in Ion-Neutral Collisions

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The observation of quantum scattering resonances in ion–atom and ion–molecule collisions has remained a formidable challenge due to the stringent energy resolution required to resolve narrow scattering features and the difficulty of reaching the *s*-wave regime in heavy systems. To date, Ba⁺/Li is the only system in which Feshbach resonances have been successfully observed in a hybrid ion trap [1]. So far, no other experiment has succeeded in detecting quantum shape resonances in ion–neutral collisions and reactions. Here, we report the first experimental observation of shape resonances in ion–neutral collisions, detected via charge-transfer reactions between helium isotopes. Charge transfer between identical isotopes can be described as an interference effect between the symmetric and antisymmetric Born–Oppenheimer potential-energy surfaces associated with nuclear exchange. The energy difference between these two potential surfaces at a given internuclear distance is directly related to the charge-hopping rate between the two atoms. In the symmetric system of identical isotopes, the elastic and charge-exchange channels are indistinguishable, giving rise to additional interference terms in the scattering cross section.

Using highly excited helium Rydberg atoms merged with ground-state helium atoms, we observed shape resonances in the elastic scattering channel, reaching collision energies just below 1 K. By further reducing the accessible collision energies by a factor of 20, we reached 10 mK and detected a sharp shape resonance at 90 mK in the charge-transfer reaction between ⁴He⁺ and ³He. The introduction of a different isotope breaks the symmetry and requires a theoretical treatment that goes beyond the Born–Oppenheimer approximation. This system therefore provides a stringent test of state-of-the-art theory, and we demonstrate agreement without free parameters, representing the first complete experimental validation of beyond-Born–Oppenheimer quantum chemistry. Beyond this benchmark, we directly measure the ionization-energy difference between ⁴He and ³He as the energy release in the reaction. Our result is consistent with the only previous determination by Herzberg [2] and constitutes the first direct measurement using this method.

As an immediate extension, we move from ion–atom to ion–molecule systems, where we have also observed resonances in the elastic scattering channel of helium-ion collisions with H₂ and HD, identifying these systems as promising candidates for the observation of Feshbach resonances.

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**Diffusion of atoms produced by photodissociation in an I₂ vapour:
pressure dependence of surface recombination and a correction of the
decay time of the fundamental mode**

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This work investigates, theoretically and experimentally, the spatio-temporal evolution of the density of iodine atoms produced in a cylindrical quartz cell containing iodine molecular gas. The atoms are generated along the axis of the cell by laser photodissociation at the wavelength 488 nm and their density is monitored using the two-photon absorption laser-induced fluorescence (TALIF) technique.

The diffusion coefficient D and the wall-recombination probability γ are determined by fitting a multimode model of atomic diffusion to experimental time variations of the atomic density recorded under various pressures. An improved formula is established for the fundamental-mode decay time, beyond the usual addition of a diffusion time and a recombination time [1]. The diffusion coefficient D of I in I₂ vapour is found equal to $0.048 \pm 0.009 \text{ m}^2\text{s}^{-1}$ at 10 Pa, while the wall-recombination coefficient γ decreases from 0.25 to 0.05 when the pressure increases from 2.7 to 31 Pa.

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Improving an ^{87}Sr Clock Atom Interferometer with Squeezed States

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Long-baseline differential atom interferometers, like those being developed for the Atom Interferometer Observatory and Network (AION) project, have been proposed as a tool to detect gravitational waves and probe models of ultra-light dark matter [1]. Recently, we have demonstrated the first vertical differential atom interferometer using the milliHertz-linewidth clock transition of strontium-87 operating at quantum projection noise (QPN) limit [2]. To further increase the sensitivity of the interferometer and reduce the QPN, entangled atomic states called *squeezed states* are needed. To achieve this, ultracold atoms in an in-vacuum high-finesse cavity have been prepared, which enables a quantum non-demolition measurement of the atomic population by probing the vacuum Rabi splitting. A phenomenon, which occurs when the atoms are collectively coupled strongly to the cavity. With this technique, we aim to reach more than 20 dB of noise reduction.

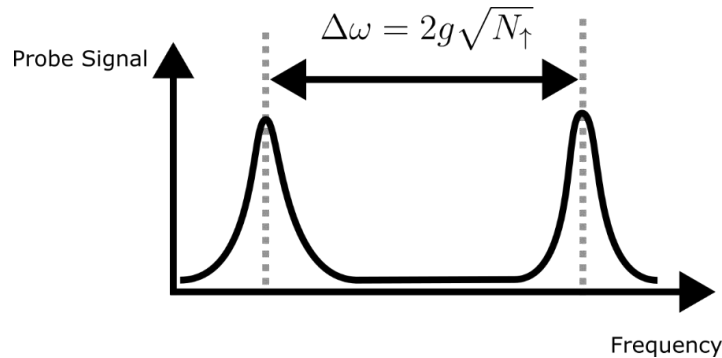


Figure 1 Vacuum Rabi Splitting. Due to the strong coupling of the cavity photons with the atoms, a frequency splitting in the cavity resonance proportional to the population of atoms is generated. Measuring the shift reveals information about the collective atomic state.

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Progress towards an experimental platform for investigating superfluid & vortex dynamics within binary BECs

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First observed in liquid helium, superfluids display bulk behaviour as a result of the cooperative action of the constituent atoms, flowing without viscosity. Quantum mixtures composed of ultracold atomic gases provide an unparalleled degree of control for the investigation of fundamental superfluid dynamics through the ability to precisely control the inter- and intra-species interactions [1], in turn allowing for the cancelling of mean field effects [2]. In particular, quantised vortices formed within these ultracold gases provide a window for investigations of energy dissipation [3] within macroscopic quantum systems (including superconductors [4]).

Investigations of these behaviours, through controlled creation and pinning of these vortices with a binary superfluid [5], may also provide insights into other beyond-mean-field effects within superfluids when quantum fluctuations are non-negligible. We present the work completed towards an experimental platform for examining superfluid and vortex dynamics within a binary Bose-Einstein condensate of ⁸⁷Rb and ⁴¹K, alongside some early simulations of vortex nucleation and dynamics within the binary superfluid.

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High-Resolution REMPI Spectroscopy for Molecular Characterization

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Resonance-Enhanced Multi-Photon Ionization (REMPI) spectroscopy provides a powerful approach for sensitive quantum state-selective detection of molecules [1]. In particular, hydrogen and its isotopologues. We investigate state-selective ionization of H₂ using UV laser pulses near 202 nm and 211 nm, targeting lines such as Q(1) 1–0 to access ground and excited vibrational states [2-3]. Previous studies have highlighted the importance of controlling internal rotational states in cold-collision experiments involving HD, H₂, and D₂ [4-5]. Further motivation comes from recent demonstrations of preparing high-vibrational states across entire molecular beams [6]. Recent progress in ultra-precise spectroscopy of the hydrogen molecule has achieved uncertainties as low as 13 kHz [7], establishing a benchmark for molecular QED tests. Although Doppler-free techniques suppress first-order Doppler shifts, further improvements require minimizing residual broadening mechanisms. In our approach, we are developing a detection system essential for performing high-resolution rovibrational spectroscopy of trapped hydrogen molecules.

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Nonlinear refractive index in warm rubidium vapor

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Warm atomic vapors have recently seen a striking revival triggered by their application in chip-scale atomic devices, such as atomic clocks and magnetometers, and in the research of squeezed light generation, quantum memories, and quantum fluids of light. In all these applications warm atomic vapors are a media of choice since they allow for a precise control of the linear and nonlinear index of refraction through optical manipulation of the atomic states. Nonlinear effects in atomic vapors emerge at very low powers which enables the observation of nonlinear optical phenomena using low-intensity continuous wave lasers, but simultaneously means that saturation effects must routinely be considered. Surprisingly, only a handful of experiments regarding the measurement of nonlinear refractive index of rubidium vapor can be found in the literature [1], whereas the theoretical works have managed to reproduce the measured values only semi-quantitatively [2], highlighting the need for both more detailed theoretical modeling as well as an improved experiment.

In this work we present results of the theoretical and experimental investigation of the nonlinear refractive index of warm rubidium (Rb) atomic vapor. We use the density matrix formalism and optical Bloch equations for calculating the optical response of multilevel Rb atoms (including hyperfine levels) to laser light. We provide Python scripts for all theoretical calculations presented in this work, including the refractive index calculation, that can readily be used in practical implementations for real-time simulations of the (non)linear refractive index of Rb vapor including the effects of Doppler broadening, transit time broadening, pressure broadening, saturation, optical pumping, and inelastic collisions. We employ an interferometric technique to measure the refractive index of ⁸⁷Rb vapor as a function of laser frequency and power, and show good quantitative agreement with theoretical simulations [3].

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Excitation of a degenerate Rb gas in a shell trap

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For more than a decade, the rubidium 87 quantum gas experiment at Laboratoire de Physique des Lasers is studying the superfluid dynamics on a shell geometry: degenerate gas samples are produced in a quadrupole magnetic trap dressed with a radio frequency field. In this configuration, the atoms are located near an isomagnetic ellipsoidal surface of the inhomogeneous static field. In the presence of gravity, this ellipsoidal trap allows a two-dimensional confinement in a smooth and highly tunable potential. This has allowed the study of collective modes [1] or the observation of fast rotation [2]. Also, It has been demonstrated [3] that gravity can be partially compensated so that the superfluid explores a larger portion of the trap. This now allows us to study of out-of-equilibrium dynamics of a superfluid on a curved surface well beyond the harmonic trap approximation: we apply a strong excitation of the gas and monitor the nucleation of vortices in the cloud (see figure 1). As in 2D a vortex corresponds to a point where the density of the superfluid vanishes, with a size fixed by the healing length – a few hundreds of nanometers in atomic BECs – we rely on the matter-wave lensing technique [4] and time of flight to enlarge the size of the cloud and detect vortices (see figure 1).

In parallel, we are engaged in a deep refurbishment of the core of the experimental setup: we are working on a new absorption imaging system with better optical resolution and explore the $5s\ ^2S_{1/2} \rightarrow 6p\ ^2P_{3/2}$ transition at 420 nm as a potential probe transition.

Latest developments will be presented at the conference.

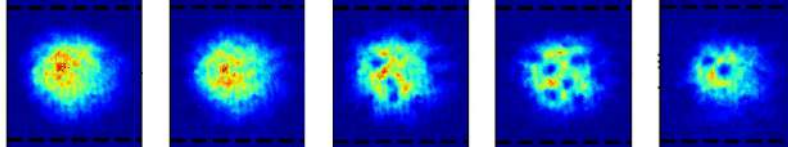


Figure 1: Images of the atomic cloud with increasing amplitude of excitation.

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Hollow-Core Fibre Platform for Sr Optical Clocks

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Optical lattice clocks (OLCs) rely on the ultra-precise interrogation of narrow optical transitions, currently achieving inaccuracies at the 10^{-18} level [1]. Present-day optical clock systems typically require atomic ovens operating above 700 K and strong time-dependent magnetic fields, making spatial separation between atom preparation and interrogation regions highly desirable. In conventional OLCs, a laser stabilized to an ultra-stable optical cavity maintains frequency coherence while new samples of ultracold atoms are sequentially prepared and loaded within the clock cycle.

One promising approach toward continuous optical clock operation is superradiant lasing on the clock transition, where an atomic ensemble directly emits light at the clock frequency [2]. Our work contributes to this direction through the development of a hollow-core fibre platform for continuous delivery and manipulation of ultracold atoms [3].

We are developing an experimental platform for trapping ^{88}Sr atoms in a two-stage magneto-optical trap and transporting them through a hollow-core crystal fibre using an optical dipole guide. As an important milestone, we have successfully observed the first-stage MOT at $^1\text{S}_0$ - $^1\text{P}_1$ transition (461 nm) in the presence of the hollow-core fibre integrated into the vacuum system. This demonstrates compatibility of the fibre assembly with laser cooling and trapping of Sr atoms and represents a key step toward fibre-assisted atom transport.

Current work focuses on implementing second-stage cooling of Sr atoms at $^1\text{S}_0$ - $^3\text{P}_1$ transition at 689 nm and efficient light coupling into an 8 cm long hollow-core fibre. We aim to optimize atom loading directly from $^1\text{S}_0$ - $^3\text{P}_1$ MOT to a moving lattice potential operating at magic wavelength at 813 nm. In the next stage, we plan to implement methods for reduce heating during transport, and extend atom lifetime inside the fibre using targeted cooling schemes and moving optical lattices.

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Towards active superradiance clock with cold strontium atoms

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Optical atomic clocks are widely used in physics as extremely precise frequency standards and as highly sensitive tools for probing fundamental physics [1]. The current generation of passive optical clocks, despite their impressive performance, is limited by ultrastable clock lasers. An active optical atomic clock based on the phenomenon of superradiance can overcome these limitations [2] and, in principle, enable measurements that are orders of magnitude more sensitive.

We would like to present a project aiming to construct continuous active optical atomic clock with strontium atoms [3]. The vacuum system is made of non magnetic materials like titanium, copper, glass and aluminum ensuring low magnetic susceptibility. Water cooled vacuum magnetic coils are designed with an excellent optical access in mind and with precise magnetic field control up to 300 G. The coils are designed to be installed near the center of the main vacuum chamber, inside high finesse optical resonator for superradiance. Additionally, we present a current control driver, that allows to stabilize current up to 150 A and to switch current direction in ms time scale. The whole system is designed for excellent control over the environment in order to utilize both 88 and 87 isotope of strontium atoms.

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Analysis and Mitigation of Bandwidth Nonlinearity in CRDS for High-Accuracy Optical Gas Metrology

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Many high-accuracy spectroscopic applications such as, greenhouse gas monitoring, isotope ratio analysis, optical thermometry, primary gas standards require precise measurement of spectral line shapes and intensities at per mil (‰) level. Cavity ring-down spectroscopy (CRDS) [1] is widely used in this context due to its high sensitivity, precision (below 0.01‰) and calibration-free operation; however, its accuracy is often limited to around 5‰ due to inaccuracies in light intensity measurements.

We observe that, as long as the light is turned off quickly and a single cavity mode is excited, the main limitation to the accuracy in CRDS comes from nonlinearity in the detection system, including the detector, digitizer, and electronics along the way. This distortion in detection band causes significant deviations from an ideal exponential shape, leading to incorrect fitted time constants and structured, non-random fit residuals.

To overcome this problem, we developed a correction methodology in which the transfer function (TF) of the complete detection system is measured using a simple optical setup based on heterodyne detection of two laser beams with a controlled frequency detuning between them. An analytical expression for the TF was derived and validated against numerous experimentally measured TFs obtained with different detection systems. This analytical TF is then incorporated into the fitting procedure: instead of using a simple single-exponential decay, the theoretical decay function is convolved with the time-domain TF model, and the resulting signal is fitted to the measured ring-downs. This approach enables more accurate extraction of decay time constants without requiring any modifications to the existing CRDS setup.

We validate our method using the CO R(23) 3–0 transition, achieving line-intensity accuracy at the permil level, in agreement with independent spectroscopic techniques such as cavity mode dispersion spectroscopy (CMDS) [2] and heterodyne cavity ring-down spectroscopy (HCRDS) [3] which are inherently immune to detection system nonlinearities. Thus, correcting for detection system nonlinearity enables conventional CRDS to reach accuracy levels previously attainable only with more advanced techniques [2, 3, 4], making it a competitive tool for high-accuracy optical gas metrology.

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Heterodyne Cavity Ring-Down Spectroscopy for Accurate HD Line-Shape Analysis

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Molecular hydrogen (H_2) and its isotopologues are widely regarded as benchmark systems for validation of spectral line-shape models and testing quantum electrodynamics (QED) calculations. Accurate hydrogen line intensities, line positions, and collision-induced line-shape parameters under varying thermodynamic conditions are also crucial in astrophysics for modelling of atmosphere of exoplanets and stars.

Reaching high experimental accuracy is a challenge in line-shape studies. Commonly used cavity ring-down spectroscopy (CRDS) provides ultra-high precision ($<0.01\%$) but its accuracy is typically limited to $\sim 5\%$ due to inaccuracies in light intensity measurements. To overcome this limitation, we developed a heterodyne cavity ring-down spectroscopy (HCRDS) method [1]. This approach exploits the optical frequency information contained in the cavity's electromagnetic field by heterodyne detection of the ring-down signals, followed by Fourier analysis. It achieves sub-per-mil accuracy, which has been validated against *ab initio* CO line intensities.

Using HCRDS, we analyzed the P(3) 2-0 transition of HD molecule. A multi-spectrum fit was performed to both absorption and dispersion HCRDS spectra using various collision line-shape models. Generally, the speed-dependent hard collision profile (SDHCP) or the more advanced β -corrected SDHCP (β -SDHCP) [2] are commonly used to analyze molecular hydrogen spectra at low pressures, while speed-dependent billiard-ball profile (SDBBP) [3] is considered at intermediate pressures (around atmospheric conditions). However, our results show that even at very low hydrogen pressures (up to 0.05 atm), SDBBP performs better than β -SDHCP and going beyond the β -SDHCP provides higher-accuracy of the line intensity. Fixing of one of the line-shape parameters affecting the width of a collision-broadened spectral line to *ab initio* value is enough to show that β -SDHCP results deteriorate significantly, while SDBBP provides stable, high-quality fits. Note that, fixing one of these parameters is a common approach to remove the numerical correlations between them which are relatively strong for weak hydrogen lines at low and moderate pressures. In addition to achieving per-mille-level agreement with *ab initio* line intensities, we show that the SDBBP independently validates the recently determined HD line position obtained using vibrational saturation spectroscopy [4]. Despite low pressures and the resulting partial correlations between line position and shift, we show that fixing the position to the value from Ref. [4] does not degrade the fit quality when the SDBBP is used.

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Ground-state cooling of mixed-ion crystals in the intermediate Lamb–Dicke regime

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Precision measurements are one of the approaches in the search for new physics. Using highly charged ions (HCIs) offers reduced systematic effects and an increased number of available transitions for generalized King plot analyses [1]. Ground-state cooling of motional modes in mixed-species ion crystals is a key requirement for implementing quantum logic spectroscopy of HCIs [2]. Building on our demonstrated ground-state cooling of both single Be^+ ions and two-ion Be^+ crystals using a combination of continuous sideband cooling on higher-order sidebands and pulsed sideband cooling, we extend these techniques to systems involving HCIs, where we investigate the impact of varying charge states and charge-to-mass ratios on cooling performance using $\text{Be}^+-\text{Ar}^{n+}$ and $\text{Be}^+-\text{Xe}^{n+}$ crystals with HCI charge states ranging from 10^+ to 18^+ .

Since our current trap operates in an intermediate Lamb–Dicke regime with η up to 0.7 for the mixed species crystals, we explore adapted cooling strategies that remain effective outside the Lamb–Dicke limit. We demonstrate successful ground-state cooling of the axial modes in $\text{Be}^+-\text{Xe}^{17+}$ crystals, where the favorable charge-to-mass ratio enables strong coupling of the shared motional modes. We further report our progress toward achieving ground-state cooling of a $\text{Be}^+-\text{Ar}^{13+}$ crystal under these conditions, including characterization and optimization of cooling sequences. These advances represent an essential step toward full quantum logic spectroscopy of HCIs and the high-precision tests of fundamental physics that they enable.

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AQuRA, a prototype industrial transportable optical clock

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As laboratory optical clocks now reach accuracies on the order of 10^{-18} , the development of transportable optical clocks [1] [2] [3] will allow for applications such as clock comparisons without fiber or satellite links, chronometric geodesy, network synchronization, and tests of fundamental physics. In this context the AQuRA project gathers a consortium of European industries, national metrology institutes and academia, with the goal to develop a European prototype of an industrial transportable optical lattice clock with Sr atoms, aiming for a fractional instability and uncertainty of $5 \cdot 10^{-18}$. Here, we report on the design, assembly and integration of the clock modules in a set of four 19" racks, comprising:

- The physics package (CNRS/LTE and UMK): a vacuum system containing a Sr source, a science chamber to trap and probe the atoms and its optical and electro-magnetic environment.
- Laser sources provided by industry partners: a 461 nm laser based on frequency doubling of a VECSEL (VEX); the 689 nm and 698 nm laser sources based on harmonic sum-frequency generation (NKT); and the 813 nm lattice laser based on difference frequency generation (EXA). Laser light is distributed through robotically manufactured optical circuit boards, and the clock sequence is driven by an FPGA-based electronics controlling analog, digital and radio-frequency signals (UvA).
- A frequency comb, extended by a super-continuum module and referenced to a high-finesse ultra-stable cavity (MEN).

At the time of the writing, we have integrated all the clock modules and achieved the first and second-stage cooling of strontium. After completion, the system will be transported to Toruń (Poland) for VLBI applications and then characterized at PTB (Germany).

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Isotope shift spectroscopy in mercury vapours for new physics search

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In the last decade, isotope shift spectroscopy has emerged as a powerful tool for probing new physics beyond the Standard Model through precision measurements in atomic systems. It is well known that the isotope shift can be decomposed into mass and field contributions, which are expected to produce a linear correlation between mass-scaled isotope shifts for different transitions of a given atomic species, in the so-called King plot [1]. However, higher-order effects, such as quadratic field shifts, nuclear deformation, and potential contributions from new physics, can induce slight deviations from linearity. More particularly, new physics contributions have been shown to arise from a hypothetical attractive force between neutrons of the atomic nucleus and bound electrons, modeled by a Yukawa-like potential and mediated by a new boson [2].

In this work, we present a high-precision experimental investigation of isotope shifts in mercury vapors, focusing on the intercombination transition $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1$ at 253.7 nm. Measurements were performed on the five bosonic isotopes of mercury (^{196}Hg , ^{198}Hg , ^{200}Hg , ^{202}Hg , ^{204}Hg), using frequency-comb-referenced wavelength-modulated saturated absorption spectroscopy [3, 4]. Absolute transition frequencies were determined with fractional uncertainties at the 10^{-12} level, allowing a significant improvement in isotope-shift accuracy compared to previous studies. By combining our data set with existing measurements of the $6s6p\ ^3P_2 \rightarrow 6s7s\ ^3S_1$ transition at 546 nm [5], we constructed a King plot whose analysis reveals a nonlinearity with a statistical significance of 4.6σ . This result is particularly relevant because even-even mercury isotopes are characterized by nearly spherical nuclear shapes [6], a circumstance that leads to a significant reduction of nuclear deformation contributions compared to other systems such as ytterbium [7, 8].

This study proposes mercury as a highly promising system for precision isotope shift spectroscopy and for constraining new physics beyond the Standard Model. Using the residuals from the King-plot analysis, we set an upper bound on the coupling strength of a hypothetical new interaction at the level of 5.2×10^{-12} , in the massless limit of the new boson.

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Precision spectroscopy of ethylene at 6.79 μm : absolute frequency calibration for muonic hydrogen spectroscopy in the FAMU experiment

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Characterized by a planar geometry, ethylene (C_2H_4) is the simplest alkene with only two carbon atoms, forming the typical carbon-carbon double bond. The molecule has 12 normal modes of vibration, which consist of five stretching modes and seven bending modes [1]. The ν_{12} band, arising from one of the bending vibrations, covers the spectral window between 1400 and 1500 cm^{-1} , which overlaps with the interval around the wavelength of 6.7887 μm where the hyperfine transition of the ground state of muonic hydrogen is expected to occur [2]. This interval is currently probed by the FAMU experiment, which aims to measure the ground-state hyperfine splitting in muonic hydrogen to retrieve the proton Zemach radius and probe the proton magnetic structure [3]. Therefore, the ν_{12} band offers a number of possibilities for the absolute frequency calibration of the laser system currently employed in the FAMU experiment, provided that the line center frequency of the selected C_2H_4 line is accurately known. These frequencies are listed in the HITRAN database with a quoted uncertainty between 3 and 30 MHz, whereas it would be highly desirable to reduce this uncertainty to less than 1 MHz. Driven by this strong motivation, we have developed a comb-referenced mid-infrared spectrometer to perform high-precision frequency measurements of ethylene resonances at 6.79 μm .

The spectrometer is based on a continuous wave, single mode, distributed feedback quantum cascade laser (QCL) with a maximum power of about 40 mW. One of the main challenges involved the implementation of an effective strategy for referencing the mid infrared radiation to a near infrared optical frequency comb synthesizer (OFCS). The solution of up-converting the mid-infrared radiation by means of the nonlinear process of sum frequency generation (SFG) in a AgGaS_2 crystal was adopted.

In this work, we present the first absolute frequency measurements of the $14_{1,13} \rightarrow 15_{1,14}$ component of the ν_{12} band as a function of the C_2H_4 gas pressure. A linear fit of the data allowed us to determine the zero-pressure center frequency along with the pressure shifting coefficient with unprecedented uncertainties.

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Probing Nuclear Interactions Through Isotope Shift Spectroscopy of Mercury

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Atomic mercury is a promising platform for precision tests of fundamental physics, including the search for a permanent electric dipole moment (EDM) that could shed light on the baryon asymmetry of the universe. Improved knowledge of nuclear structure is essential for interpreting and tightening EDM bounds. We perform precision isotope shift (IS) spectroscopy on the $6s^2\ ^1S_0 \rightarrow 6s\ 6p\ ^3P_1$ and $6s\ 6p\ ^3P_1 \rightarrow 6s\ 6d\ ^3D_J$ ($J=1, 2$) transitions in neutral mercury, covering all five even isotopes. Using laser-cooled atoms, we reach uncertainties of 20 kHz ($\sim 2 \times 10^{-6}$ fractional). A King plot analysis reveals a 4.9σ nonlinearity, indicating higher-order field shifts linked to nuclear structure. These results benchmark nuclear models relevant for EDM searches and combined with further IS studies, opens a pathway to probe new electron–neutron interactions. We also demonstrate loading mercury into an optical dipole trap, enabling future EDM measurements on laser-cooled atoms.

High-Resolution Spectroscopy of Ca Rydberg Stark States and Determination of the Ca^+ Dipole and Quadrupole Polarizabilities

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Rydberg atoms provide a sensitive probe of the electrostatic properties of their ionic core: the weakly bound outer electron behaves nearly hydrogenically and generates an electric field that polarises the ionic core. High- ℓ ($\ell \geq 4$) Rydberg states are shifted relative to the hydrogenic value by an amount dictated by the core polarisability, $\Delta E = -\frac{1}{2}\alpha_d\langle r^{-4} \rangle - \frac{1}{2}\alpha_q\langle r^{-6} \rangle$ [1]. Measuring accurately these energy shifts for multiple Rydberg states [2] allows one to retrieve the dipole and quadrupole polarizabilities of the isolated ion. We exploit this property to extract the dipole (α_d) and quadrupole (α_q) polarizabilities of the Ca^+ ion, quantities that are challenging to precisely measure with the bare, isolated ion, but are critical to evaluate the blackbody radiation shift of the Ca^+ optical clock transition [3].

To perform the high resolution spectroscopy of the Rydberg states of Ca required to determine ionic polarizabilities, neutral Ca atoms are laser cooled and trapped in a magneto-optical trap (MOT) forming an ultracold atomic cloud (~ 1 mK) [4]. An electric field is applied (~ 1 V/cm) to induce a dc Stark effect. The trapped calcium atoms are then excited to Rydberg Stark states using a resonant three-color, three-photon excitation scheme. Following excitation, the Rydberg atoms are field-ionized and the Ca^+ ions are guided to a channel electron multiplier. By scanning the frequency of the third excitation laser, we obtain the energy spectrum of the Rydberg Stark states at a given electric field. Repeating the measurement for several electric fields generate Stark maps, in which the slopes, curvatures, and avoided crossings between Stark states, all depend on α_d and α_q .

We present a Ca Stark map at $n = 52$ and perform a global fit of the spectrum using the Alkali Rydberg Calculator (ARC) package [5]. The core-polarization model constrains $\ell \geq 4$ quantum defects, treating α_d and α_q as free parameters. Non-adiabatic corrections, essential for alkaline-earth systems [2], are incorporated via scaling factors k_d and k_q , calculated with ab-initio theory [6]. Our results are compared to theoretical predictions and to previous microwave measurements [2], and we discuss the long-standing discrepancy on α_q determinations.

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Further observations of the comet-tail system in $^{12}\text{C}^{17}\text{O}^+$

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The comet-tail system is the most intensively investigated band system of the CO^+ molecule. In our laboratory, we have been studying this system in the emission spectrum of the $^{12}\text{C}^{17}\text{O}^+$ isotopologue for several years. Currently, after studying the $0 - v''$ progression, where $v'' = 0, 1, 2, 3$ [1] and the $1 - v''$ progression, where $v'' = 0, 1, 2$ [2], we present the results of the rotational analysis of the $2 - v''$ progression, where $v'' = 0, 1$. Using a high-resolution Fourier-transform spectrometer, in the region of $20\,000 - 23\,500\text{ cm}^{-1}$ more than 850 spectral lines were measured with an accuracy of 0.03 cm^{-1} . As a result of the spectral analysis, molecular parameters of $A(v = 2)$ and $X(v = 0, 1)$ levels were calculated. The possible influence of the $X^2\Sigma^+(v = 12)$ level on the $A^2\Pi_i(v = 2)$ level was also verified. In addition, the values of the rovibronic terms of level $A^2\Pi_i(v = 2)$ were determined.

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Dual Laser Locking for Ytterbium via Modulation Transfer Spectroscopy

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Compact and efficient laser locking is essential for scalable optical platforms controlling neutral atoms. We present a dual-frequency stabilization scheme based on modulation transfer spectroscopy (MTS), enabling locking of a 399 nm laser for laser cooling and trapping of ytterbium (Yb) atoms in a magneto-optical trap [1], and future stabilization of a 369 nm laser for ionization of Rydberg-excited Yb atoms. MTS provides Doppler-free dispersive signals with zero background and well-defined zero-crossings, making it well suited for accurate frequency stabilization in room-temperature atomic vapors [2].

The experimental setup (Figure 1(a)) features two symmetric beam paths for the lasers to be stabilized. A collimated fiber output is split into pump and probe beams, which counterpropagate through a hollow cathode lamp where modulation transfer occurs. The pump is phase-modulated using an electro-optical modulator, and transfers the modulation to the probe via the atomic medium. The resulting signal is detected by a photodiode and demodulated to produce the error signal shown in Figure 1(b), which exhibits distinct inflection points corresponding to different ytterbium isotopes. The signal is fitted as a sum of dispersive signals with free resonance frequencies and amplitudes. We show stable locking of the 399 nm laser to the $^{174}\text{Yb } ^1S_0 \rightarrow ^1P_1$ transition, characterize the laser stability and perform a noise analysis of the signal.

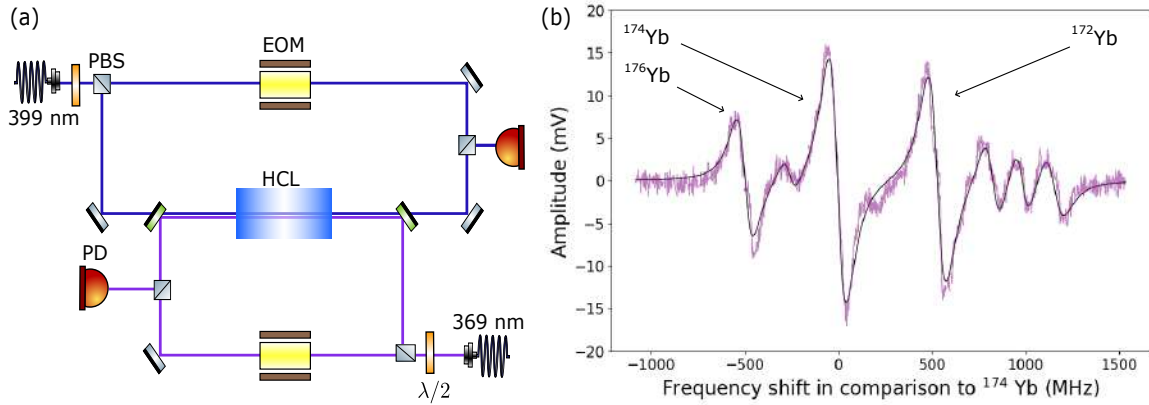


Figure 1: (a) Dual-frequency MTS experimental setup. Abbreviations: PBS – polarizing beam splitter, EOM – electro-optical modulator, HCL – hollow cathode lamp, PD – photodiode, $\lambda/2$ – half-wave plate. (b) Isotope-resolved error signal showing the $^1S_0 \rightarrow ^1P_1$ transitions of several Yb isotopes (purple data) and the corresponding fit (black curve).

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High - resolution FT-UV study of the $B^2\Sigma^+ - X^2\Sigma^+$ system of $^{12}C^{17}O^+$: $B^2\Sigma^+$, $v = 0, 1$ levels revisited

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The carbon monoxide cation (CO^+), derived from one of the most abundant molecules in the interstellar medium – CO – has been extensively studied for its dominant isotopologue. The $^{12}C^{16}O^+$ molecule has been identified both in the ISM through low-rotational transitions and in cometary spectra via the $A^2\Pi_i - X^2\Sigma^+$ system [1]. In contrast, the $^{12}C^{17}O^+$ isotopologue has not yet been detected in astrophysical environments, despite the confirmed presence of $^{12}C^{17}O$ in the ISM, even given the low natural abundance of ^{17}O ($\sim 0.04\%$).

In this work, we report high-resolution spectroscopic investigation of $^{12}C^{17}O^+$ carried out at the Materials Spectroscopy Laboratory, University of Rzeszów. The study focuses on the $B^2\Sigma^+ - X^2\Sigma^+$ electronic transition system using Fourier-transform ultraviolet (FT-UV) emission spectroscopy. About 1000 ro-vibronic transitions of the 0–0, 1, 2, 3 and 1–0, 2, 3, 4, 5 bands, were measured with absolute uncertainties ranging from 0.0050 to 0.0100 cm^{-1} .

The analysis was performed using the PGOPHER software [2], enabling the determination of accurate molecular constants and energy level values for the $X^2\Sigma^+$ ($v = 0-5$) and $B^2\Sigma^+$ ($v = 0,1$) states of the $^{12}C^{17}O^+$ isotopologue.

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Towards quantum logic spectroscopy of highly charged heavy ions for novel optical clocks

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Highly charged heavy ions, particularly hydrogen- or lithium-like species, are exceptional probes for fundamental physics. With extreme internal electromagnetic fields and forbidden hyperfine-structure transitions in the optical regime (e.g. 1019.7 nm in $^{207}\text{Pb}^{81+}$ [1]), they are highly sensitive to physics beyond the Standard Model [2 - 4]. Additionally, systematic effects from external perturbations are highly suppressed, and the atomic structure is simple. These ions are therefore excellent systems to test our understanding of nature and to realize novel high-accuracy optical clocks.

While both quantum logic spectroscopy (QLS) and optical clocks have been demonstrated with lighter HCIs [5 - 8], the realization with heavy ion species in their highest charge states remains an open challenge. State of the art measurements of electron transition energies in HCI are currently realized in storage rings with an uncertainty level in the order of 10^{-5} [9, 10].

Setups, which integrate all required ingredients, i.e. a source for highly charged heavy ions, a cryogenic Paul trap featuring extremely high vacuum, and QLS, are under development and have the potential to improve precision and accuracy by many orders of magnitude. Essentially only limited by the natural linewidth of the clock transition itself, these setups will enable unprecedented advances in studies of atomic, nuclear, and fundamental physics as well as searches for physics beyond the Standard Model.

This contribution reports on our development of a unique and versatile QLS platform for accelerator-produced highly charged heavy ions downstream of the HITRAP decelerator at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt.

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Cryogenic spectrometer - benefits and perspectives for further technical development

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Spectrometers operating in cryogenic conditions have been shown to be potent tools for fundamental physics research. The cryogenic approach paired with high vacuum technology paves a way for more precise spectroscopic instruments. We present the first cryogenic cavity-enhanced spectrometer fully operating in deep cryogenic conditions down to 4 K [1,2]. This allows for studying the gas sample in thermal equilibrium in very low temperatures. We address the external noise attenuation as well as disturbances coming from the setup itself. We achieve this using heavy copper blocks in a layered structure as well as suspending the entire optical system on thin titanium rods. The instrument can be further improved by implementing the frequency-agile rapid-scanning spectroscopy (FARS) technique as well as utilizing purely frequency based spectroscopic methods [3].

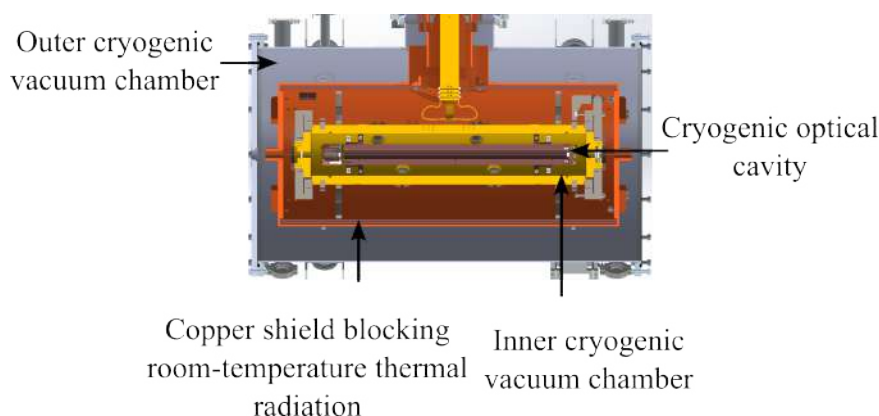


Figure 1: The design of the cavity operating in a vacuum chamber and capable of cooling all of its optical elements to temperature as low as 4 K.

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Barium fluoride deceleration using temporary ionization

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Due to their complex structure, molecules are interesting systems for applications in various fields such as quantum chemistry or precision measurements. But it also implies more difficult cooling and slowing techniques than for atoms.

This experiment on Barium Fluoride (BaF) aims at decelerating a supersonic molecular beam by using the electric force on ions (Fig.1). This force is much more intense than the dipolar force commonly used on molecules in other slowing techniques like Stark and Zeeman decelerations relying on time-varying dipole forces. Fewer space and weaker electric fields are thus required compared to these other techniques. For instance, applying a field of a few volts/cm is enough to decrease from 600m/s to almost zero velocity the ions in about 10 microseconds and over a few millimeters.

A temporary ionization is indeed required in the deceleration process, happening as follows: molecules are photo-ionized into BaF^+ in order to efficiently decelerate them thanks to an electric field pulse. Neutralization then has to be achieved by an electron capture which will happen through the collision between BaF^+ ions and a Rydberg atom beam, for which electrons are weakly bound.

This presentation will mainly focus on the study of the ion deceleration using a uniform electric field generator [1]. We will show that it allows to have a robust control on the mean velocity of the ions and to measure some properties of the ion bunches. Some collateral effects such as Coulomb repulsion between ions have also been studied. Finally, a description of the neutralization process which is currently being studied experimentally will also be presented.

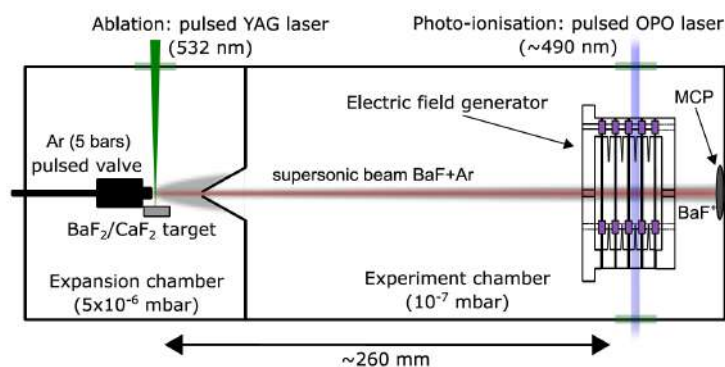


Figure 1: Schematic of the experimental setup, representing the argon supersonic expansion, the formation of BaF molecules by laser ablation, the photo-ionization of BaF into BaF^+ by a pulsed OPO laser and their detection using micro-channel plates

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Fast and slow scrambling in many-body long-range interacting systems

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Information scrambling, and its intimate relation to quantum chaos, represents one of the frontiers of research in condensed matter and many-body physics. A system which deteriorates information exponentially in time is called a fast scrambler, and the associated scrambling rate has been regarded as a quantum analog of the Lyapunov exponent, which in classical chaotic systems dictates the rate at which two initially closed trajectories diverge in phase space. Few condensed matter systems scramble fast, and, to the best of our knowledge, none saturates the bound on the quantum Lyapunov exponent, with the exception of the Sachdev–Ye–Kitaev (SYK) model. Here we investigate scrambling in the presence of long-range interactions and as a function of the initial state. We study how the spectral gap induced by long-range interactions affects the scrambling velocity of the system, depending on whether the initial state evolves inside a single subspace or multiple ones.

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Rigorous quantum scattering calculations for fundamental and atmospheric studies

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The shape of a molecular spectrum is modified by collisions occurring within the studied gas sample. On the one hand, this introduces systematic errors in the analysis of atmospheric measurements, as well as influences the accuracy of spectroscopic optical metrology. On the other hand, this line-shape manifestation of collisional effects offers a possibility for accurate studies of molecular interactions and quantum scattering, thus serving as an important tool for testing quantum mechanics for molecules and validating the high-quality theoretical calculations capable of providing *ab initio* line-shape parameters. We present our methodology and results concerning the fully quantum approach to the problem of collisional effects in the fine-structure, rotational, vibrational and electronic molecular spectra of atmospherically-relevant species – O₂ [1], CO [2, 3], HCl [4], HF and HCN [5] – perturbed by collisions with N₂ and O₂, the two most abundant constituents of the Earth's atmosphere. Despite the challenging nature of the quantum scattering problem, we show that the *ab initio* approach is capable of providing high-quality reference data useful for populating the spectroscopic databases (such as HITRAN, ExoMol or GEISA), which we previously demonstrated for the simpler case of He-perturbed spectra of H₂ [6].

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Fock-space relativistic coupled-cluster calculations of the properties of Th^{3+} nuclear clock

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Optical atomic clocks based on ultra-narrow electronic transitions have achieved fractional frequency uncertainties below the 10^{-18} level, establishing state-of-the-art precision in time and frequency metrology. However, their performance is limited by sensitivity to external electromagnetic perturbations. Nuclear clocks offer a promising alternative, as nuclear transitions are largely shielded by the surrounding electron cloud and are therefore expected to exhibit reduced systematic shifts and improved long-term stability [1]. In addition, their enhanced sensitivity to variation of fundamental constants makes them attractive candidates for tests of physics beyond the Standard Model [2]. The low-energy nuclear isomeric transition in ^{229}Th has made thorium-based systems particularly promising for realizing nuclear clocks [3]. In this work, we present a systematic study of atomic and clock-transition related properties of Th^{3+} using relativistic coupled-cluster theory [4-6]. We compute excitation energies of low-lying states, electric dipole (E1), electric quadrupole (E2), and magnetic dipole (M1) transition amplitudes, hyperfine structure constants, static electric dipole polarizabilities, and isotope-shift parameters relevant to the nuclear clock transition. These quantities are essential for estimating the lifetime of the nuclear isomeric state, extracting nuclear magnetic dipole and electric quadrupole moments, and evaluating sensitivity to external perturbations. To improve accuracy, we incorporate Breit interaction, quantum electrodynamical corrections, and higher-order correlation effects from perturbative triples. Our results show good agreement with available experimental and theoretical data, demonstrating the importance of relativistic and correlation effects in precision calculations of Th^{3+} . The present work provides important theoretical inputs for ongoing experimental efforts toward realization of thorium-based nuclear clocks and their applications in precision metrology and fundamental physics.

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Optical Dipole Trapping of Laser Cooled Mercury Atoms for Precision Physics

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Mercury, as the heaviest non-radioactive element amenable to direct laser cooling, is a promising platform for searches for a permanent atomic electric dipole moment (EDM). Such searches are motivated in part by the baryon asymmetry of the universe, since the observation of a permanent EDM would indicate new sources of CP violation beyond the Standard Model.

In addition, owing to its heavy nucleus and several naturally occurring isotopes, mercury enables isotope-shift spectroscopy that connect precision spectroscopy with nuclear structure and interaction studies [1].

We report on recent improvements and upgrades to the machine for transferring magneto-optically trapped mercury atoms to a high-power optical dipole trap, paving the way toward degenerate quantum gases of mercury and next-generation atomic EDM searches.

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CPT Test in the Lepton Sector – The LSYM Experiment

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LSYM is a cryogenic Penning trap experiment designed to test the symmetry of matter and antimatter. Specifically, we will investigate a hypothetical charge-to-mass ratio difference $\Delta \left| \frac{q}{m} \right|$ and g -factor difference Δg of electron and positron. The goal is to provide the most stringent test of CPT in the lepton sector, aiming for a relative precision of 5×10^{-14} . To this end, we co-trap a single positron and a bound electron in a ${}^4\text{He}^+$ ion and compare their spin precession frequency coherently.

To avoid relativistic shifts at this level of precision, the positron needs to be cooled to its motional ground state in the trap. The cyclotron motion at 140GHz cools via synchrotron radiation until it reaches equilibrium with the black-body radiation in the trap. To reach the ground-state in the cyclotron as well as the axial degree of freedom the whole trap chamber has to be cooled to about 300 mK and a cavity-assisted sideband cooling technique has to be developed, which imposes strict requirements on the millimeter-wave system.

I will present some key features as well as the current status of the experiment.

Towards State Preparation and Precision Spectroscopy of Weakly-Bound H_2^+

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The weakly-bound, high-vibrational states of H_2^+ [1] exhibit ortho-para mixing[2], a rarely observed phenomenon in molecular physics, that would allow to benchmark the effect of the nuclear spin in QED calculations. In addition, these states possess an enhanced sensitivity to the proton-to-electron mass ratio, making them attractive targets for precise determinations of this fundamental constant. We present an experimental approach to state-selectively prepare H_2^+ ions in these states, inject them into a radio-frequency ion trap, sympathetically cool them with Be^+ , and interrogate them via precision millimeter-wave spectroscopy.

Central to this effort is a specialized wire trap designed for high transmission of millimeter waves and an open endcap aperture to accommodate ion injection. State preparation is achieved through Mass-Analyzed Threshold Ionization (MATI)[3], which produces ~ 100 state-selected ions per pulse at a 10 Hz repetition rate. Starting from the ground state of H_2 and using a step-wise 3-photon excitation via ion-pair states, the H_2 bond length is gradually increased to maximize the excitation probability of the weakly-bound states of H_2^+ . While this method requires a vacuum-ultraviolet laser source, we also explore a complementary pathway based on electron-impact ionization of metastable triplet states, which can be used to produce H_2^+ ions in low vibrational levels. State-selected ions are energy-discriminated and extracted from the molecular beam prior to trap loading using an electrostatic quadrupole bender.

The rapid state preparation facilitates efficient, destructive detection of spectroscopic transitions through selective photodissociation, reducing the dead time associated with reloading the ion trap between measurements.

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High-accuracy optical spectroscopy of a single molecular ion in a Penning trap

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Laser spectroscopy of cold particles confined in Penning traps has so far been performed on single laser-cooled atomic ions [1] or on thermally cooled single atomic ions [2]. In the first case, sub-Doppler resolution has been achieved, while in the latter case not. Here, we present a major new development: the first sub-Doppler optical spectroscopy of a non-laser-coolable ion, specifically a molecular ion. The spectroscopy is non-destructive.

We chose the heteronuclear molecular hydrogen ion HD^+ for three main reasons. First, the properties of this ion have been computed ab initio with high precision so that predictions are available [3, 4]. Second, it has been extensively studied experimentally with high precision in radio-frequency (r.f.) traps [5] and fractional accuracies of $10^{-11} - 10^{-12}$ have been obtained. Third, HD^+ is a proxy for H_2^+ and its antimatter version, $\overline{\text{H}}_2^-$. A comparison of rovibrational transition frequencies of these two molecules could lead to strongly improved tests of CPT invariance [6, 7].

Our experiment was performed on a single molecule, thermally cooled to 4 K axial temperature in the cryogenic Penning trap ALPHATRAP, in a 4 T field. To enable optical frequency metrology, the facility was complemented by a suite consisting of lasers, reference cavity, frequency comb, hydrogen maser and calibration via common-view GNSS. Extending our recent study of electron-spin resonance [8], we studied the overtone transition from the ground rovibrational level ($v = 0, N = 0$) to the level ($v' = 5, N' = 1$), at 260 THz. The occurrence of the transition is detected nondestructively by probing whether, after a laser pulse, the ion temporarily enters the level ($v'' = 0, N'' = 1$) in the course of its spontaneous decay back to the initial state (0, 0). The probing is performed by attempting to flip the electron spin of the molecule while in (0, 1) by irradiation of a resonant microwave pulse. Afterwards, the electron-spin state is detected nondestructively via the continuous Stern-Gerlach effect.

We observed that the spectroscopy occurred in the Dicke regime, with a ≈ 1 kHz wide carrier resonance. The line center statistical uncertainties were $u_{\text{stat}} \approx 0.1$ kHz [4×10^{-13}]. A total of 8 hyperfine structure components of the rovibrational transition were observed, and their optical frequencies f_i were measured. The systematic uncertainties were at the level of $u_{\text{sys}}(f_i) \approx 0.1$ kHz. Our results for the differences $f_i - f_j$ can be compared to ab-initio precision calculations of the spin structure.

The achieved total frequency uncertainty $u_{\text{tot}}(f_i)/f_i < 1 \times 10^{-12}$ is competitive with current r.f. trap results and is also at a level that would make a CPT test on $\text{H}_2^+/\overline{\text{H}}_2^-$ competitive.

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Towards a scalable ion trap architecture - Trapping 2D ion arrays in a surface penning trap

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Trapped ion systems are a leading platform for quantum information processing, yet scaling conventional radio frequency (RF) Paul traps remains hindered by power dissipation, driven micromotion, and the confinement of ions to motion along the RF null, typically restricting transport to a one-dimensional trajectory [1]. To address these challenges, we utilize microfabricated Penning traps, which employ static electric and magnetic fields for confinement. This architecture eliminates the need for strong radio frequency fields and specialized junctions, enabling seamless and arbitrary three-dimensional transport. Such flexibility is a critical requirement for a scalable Penning Quantum Charge Coupled Device architecture.

This approach was recently validated at ETH Zurich with the experimental realization of the world's first microfabricated surface Penning trap using beryllium ions [2, 3]. This prototype demonstrated full three-dimensional control over the position of the ion, highlighted by the ability to translate and stabilize a single ion 400 μm above the trap surface to suppress the effects of electric field noise, measuring heating rates amongst the lowest of any trapped ion system [4]. Notably, transport induced heating was found to be negligible, which underscores the potential of the platform for high-fidelity operations.

Building on this success, we present recent progress toward a new generation of surface electrode Penning traps designed for calcium ions $^{40}\text{Ca}^+$. The shift to calcium offers more accessible laser wavelengths, which improve compatibility with commercial laser systems and provide a richer atomic-level structure. The architecture utilizes individually controllable potential wells arranged in a two-dimensional grid to allow for the flexible reconfiguration of ion arrays.

We report on recent developments in the simultaneous transport of multiple ions and the characterization of specialized potentials for deterministically merging ions into common potential wells for multi-qubit gates. Finally, we describe ongoing work toward achieving high-fidelity single-qubit optical gates on calcium in this architecture, providing a robust foundation for parallelized quantum logic operations.

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Optical tweezers for trapped ion quantum simulations

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Quantum simulation provides insight into the dynamics of complex systems through the use of more controllable ones. We plan to combine 2-dimensional Yb^+ ion crystals in a Paul trap with optical tweezers to create a novel platform for quantum simulations [1, 2]. The hyperfine splitting of the ground state of the ions is used as a qubit, and the interactions between the qubits are mediated by the phonon modes in the ion crystal [3]. Optical tweezers provide an additional trapping potential that modifies the phonon mode spectrum of the crystal, expanding the range of accessible Hamiltonians [4, 5]. We generate high-power, off-resonant tweezers using a spatial light modulator (SLM). This enables the creation of deep, tunable trapping potentials while suppressing photon scattering. We present experimental work demonstrating an optimization routine for resonant tweezers using an SLM [6]. We further analyse the beam profile and observe coherent population trapping of the ion states. Lastly, we present the alignment and optimization of a high-power, off-resonant tweezer and explore its effect on the trapping potential.

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Optimization of two-photon absorption in three-level atom. The role of correlations, indistinguishability, and atomic parameters

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Two-photon absorption is one of the fundamental nonlinear processes in light-matter interaction [1, 2, 3, 4, 5]. In a ladder-type quantum system, it enables excitation of an upper level through the cooperative action of two photons whose combined energy matches the energy gap between the initial and final states. Since the pioneering studies of multiphoton transitions [1, 2], two-photon absorption has become an important concept in atomic, molecular, and optical physics, with applications ranging from spectroscopy and microscopy to selective excitation and quantum control [6, 7, 5, 8]. At the same time, its practical use is often limited by the weakness of nonlinear optical processes, which motivates the search for quantum states of light capable of enhancing excitation efficiency under low-intensity conditions [5, 7]. A particularly promising route is to employ nonclassical light. Correlated and entangled photon pairs generated, for example, in spontaneous parametric down-conversion and related sources offer the possibility of engineering not only the total energy of the photon pair, but also its temporal and spectral structure [9, 10, 11, 12, 13, 14]. This has led to extensive studies of how photon correlations affect excitation pathways, modify resonance conditions, and potentially improve the performance of multilevel excitation schemes compared with classical illumination [15, 16, 17, 18]. Recent advances in the generation and characterization of photon pairs make these questions especially timely [19, 20, 21].

Our work presents a comprehensive theoretical study on the optimization of two-photon excitation in a three-level atom with a ladder configuration. Using an analytical framework based on the Wigner-Weisskopf approximation and stochastic formalisms [22], we characterize the quantum states of light that maximize the population of the upper atomic state. In the paper [23], we examined this problem for spectrally distinguishable photons, where each photon was effectively associated with one atomic transition. That analysis showed that the optimal excitation strategy depends qualitatively on the relation between the lifetimes of the excited states and the values of the atomic transition frequencies.

We would like to show also the complementary and physically distinct situation in which the two photons are spectrally indistinguishable, so that each of them can excite either of the two atomic transitions. This changes the structure of the absorption process in an essential way, because the two excitation pathways become quantum-mechanically indistinguishable and interfere. Consequently, the problem is not a simple extension of the distinguishable-photon case. Instead, it requires understanding how bosonic symmetrization and interference reshape the optimal temporal and spectral properties of the input field, and how these effects depend on the atomic parameters.

Finally, the ideal theoretical states are compared with experimentally accessible light sources, including Gaussian product states, temporally correlated Gaussian pulses, and coherent light. Our results provide practical benchmarks for designing efficient light-matter interfaces in quantum technologies and non-linear spectroscopy.

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Integrated Photonic Devices for Hybrid Cavity QED with Rydberg Atoms and Superconducting Circuits

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The implementation of coherent interfaces between neutral ‘Rydberg’ atom quantum processors and superconducting circuits offers a range of opportunities for hybrid quantum information processing. These include, e.g., possibilities to exploit optical photons to prepare the quantum state of a superconducting qubit in an interaction mediated by a Rydberg atom, and the realisation of long-coherence-time atomic quantum memories for superconducting processors [1]. Recently, coherent interfaces have been demonstrated between atoms in Rydberg states and superconducting co-planar waveguide resonators operated at temperatures < 4 K [2 - 4]. However, to extend this work to lower temperatures, as required for the operation of superconducting qubits, i.e., ~ 100 mK, it will be necessary to reduce line-of-sight optical access and move from free-space propagation of the laser beams used for Rydberg-state excitation to, e.g., integrated photonic devices. We present here the design and optical characterisation of a photonic chip with a grating input-coupler, a waveguide, and a grating output-coupler suitable for use in hybrid cavity QED experiments of this kind. The sub-wavelength photonic structures on this silicon nitride chip enable the formation of a directed beam at the output. The chip is designed to operate at 786 nm and is therefore suitable for experiments with helium atoms excited to Rydberg states using the $1s2s\ ^3S_1 \rightarrow 1s3p\ ^3P_2 \rightarrow 1sns\ ^3S/1snd\ ^3D$ two-colour two-photon scheme. To manage effects of charge build-up and stray electric fields, the chip is coated with indium tin oxide (ITO) [5, 6]. The effects of this coating have been accounted for in the optimisation of the optical properties of the photonic structures.

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Benchmarking a machine-learning differential equation on a neutral-atom logical processor

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We report on a performance comparison between physical and logical computations on a prototypical machine-learning application: solving differential equations using quantum kernel methods. The algorithm is implemented on an atom-based logical quantum processor, both at the physical and logical levels. We show that the kernel estimated from the logical implementation performs better than its physical counterpart on relevant metrics. We observe how such performance improvement can be traced back to specific noise-induced errors detected by the chosen encoding. We apply the computed quantum kernel to the task of solving differential equations, confirming how the superior performance of a logical quantum kernel is retained also at an end-to-end applicative level.

Towards Fault-Tolerant Quantum Computing using Neutral Atoms

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Over the last years, the field of quantum computing has witnessed a rapid growth towards fault-tolerant quantum computing. Recent breakthroughs have been achieved on various quantum processor architectures, such as ones based on superconducting circuits, ion traps, and neutral atoms [1–3]. At Pasqal, we developed an atom-based logical quantum processor, and we report on the progress towards fault-tolerant preparation of logical states. We first characterize our qubits and exhibit a relaxation time $T_1 = 5.0(2)$ s and a coherence time under dynamical decoupling $T_2 = 1.49(8)$ s. We then describe the fidelity of the different unitary operations – namely coherent atom transport, single-qubit gates and two-qubit gates. We demonstrate a single qubit gate fidelity of 99.956(8)% and a two-qubit gate fidelity of 98.7(2)% via randomized benchmarking [4, 5]. We then detail the architecture of our logical processor, which is based on a zoning approach [6–8], where regions of space are dedicated to specific operations. Next, we demonstrate the ability of our processor to prepare logical qubits in a fault-tolerant fashion. We encode two logical qubits into four physical qubits with the $[[4, 2, 2]]$ quantum error-detecting code [9]. We use a flag qubit to detect and discard faulty runs, then post-select on parity to improve logical state fidelity.

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Mediating entangling gates between polar molecules using microwave dressed Rydberg atoms

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We propose a scheme for mediating many simultaneous entangling gates between pairs of polar molecules using Rydberg atoms. By using microwave drives, the dipolar interactions between Rydberg atoms are nullified. Using the freedom left in the microwave dressing parameters, the Rydberg van der Waals interactions are minimized and the Rydberg-molecule interaction is tuned into resonance, allowing for the mediation of a modified SWAP gate between molecules. Due to the minimisation of interactions between Rydberg atoms, many such gates can be performed simultaneously in a large hybrid array of atoms and polar molecules.

In the example of mediating gates between $^{23}\text{Na}^{133}\text{Cs}$ molecules with ^{133}Cs atoms, the gate is more than two orders of magnitude faster than an equivalent direct molecule-molecule gate, while the infidelity is limited to the 10^{-2} level by decay of the Rydberg states and the motion of the atom and molecules at a trapping frequency of $\omega/2\pi = 300$ kHz.

Four-Wave Mixing in Warm Vapor for Nonclassical State Engineering via the Coherent Superposition of Photon Addition and Subtraction

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Non-Gaussian state engineering is a central challenge in continuous-variable quantum optics, since non-Gaussian operations such as photon addition and photon subtraction cannot be generated by Gaussian transformations alone [1]. A particularly versatile operation is the Lee–Nha coherent superposition $t\hat{a} + r\hat{a}^\dagger$, which combines subtraction-like and addition-like actions in a single conditional process [2,3]. Realizing this operation in a compact physical platform would provide a direct route to heralded non-Gaussian light, a key resource for quantum-state engineering, entanglement distillation, quantum-enhanced sensing, and universal continuous-variable quantum information processing. Compared with schemes that interfere separate photon-addition and photon-subtraction elements, a single-medium implementation can reduce experimental complexity while preserving the relative phase coherence between the two pathways.

We propose a warm-vapor four-wave-mixing scheme that realizes this physics in a double- Λ atomic medium. The central mechanism is that the same medium supports two coherent pathways into a common output mode: a Raman-assisted frequency-conversion process, which provides the subtraction-like contribution, and a parametric pair-generation process, which provides the addition-like contribution. When these pathways are mode matched, their probability amplitudes interfere coherently, yielding an effective addition–subtraction superposition within a single propagation stage rather than through multiple interferometric elements.

We develop a quantum input–output theory for the vapor medium, in which the Doppler-averaged atomic response determines the gain, loss, phase shifts, and mode mixing of the weak fields. By quantizing the resulting two-mode transformation and including the required vacuum noise channels, we show that the conversion and pair-generation pathways can be balanced while maintaining phase coherence under realistic warm-vapor conditions. Upon heralding, the output state exhibits Wigner-function negativity, demonstrating that the medium can implement a genuinely non-Gaussian conditional operation rather than simple amplification, attenuation, or frequency conversion.

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Digital-twin of a neutral-atom quantum processor for fault-tolerant quantum computing

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The past few years have seen neutral-atom-based quantum processors become one of the leading architectures in the race for realizing fault-tolerant quantum computing [1, 2]. This is in part thanks to recent technical advancements [3–5], but also to the development in parallel of the theoretical protocols through which the relevant atom-light interactions can be carried out [6, 7]. As part of our efforts at Pasqal to develop a neutral-atom-based logical quantum processor, we have carried out simulations of the digital operations implemented on our platform that incorporate the different experimental sources of error typically seen. The noise models built for this allow us to obtain a very good agreement with experimental data for initialization of the atoms as qubits and various unitary operations (single-, two-qubit gates, and coherent atom transport). Using these simulations has allowed us to identify key points of improvement and ways to optimize these operations as part of ongoing efforts to prepare high-fidelity logical qubits in a fault-tolerant fashion.

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Physical Layer Precursors of the Quantum Internet of Things (Q-IoT)

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The subject of the presentation will be the current state of research conducted in the laboratory of the Institute Materials Research and Quantum Engineering at the Poznan University of Technology, within the framework of an Interdisciplinary Rector's Grant. The primary objective of the project is the development of selected aspects of quantum technologies relevant to applications in the Quantum Internet of Things (Q-IoT), including the design of physical precursors of Q-IoT comprising: a layer of quantum high-precision sensors for electromagnetic fields, temperature, strain, and other physical quantities, as well as a layer of quantum security. Construction of a universal quantum microscope for continuous-wave optically detected magnetic resonance (cw-ODMR) measurements and its adaptation for the use as a quantum sensor of magnetic field and temperature will be presented [1].

The results of studies on selected atomic species in terms of their applicability in quantum technologies (in particular, in quantum sensing or quantum memories) will be discussed. The criteria for the suitability of atoms for quantum technologies primarily include the potential for efficient laser cooling; the development of cooling schemes can be achieved using complementary spectroscopic studies and semi-empirical analysis [2].

To enhance IoT hardware security, an OSHW QRNG demonstrator was developed under an Interdisciplinary Rector's Grant, integrating analog quantum modules (utilizing beam splitters or SiPM statistics) with a RISC-V system on FPGA. Collectively, the hardware and its virtualized environment constitute a comprehensive research workstation, offering a new approach to hardware security and trust within the Q-IoT ecosystem. This integration fosters synergy between physics and computer engineering while evaluating trade-offs with commercial QRNGs to define optimal security criteria for cost-sensitive IoT applications [3].

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UMK26 - A new exchange tuned exchange-correlation functional for DFT with superior performance

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Density Functional Theory (DFT) has been the primary workhorse of quantum chemical simulations, thanks to the practical trade-off it offers between computational cost and accuracy. Increasing the accuracy and efficiency of DFT has great scope in widening its applicability and aiding material science research. Though DFT is an accurate theory, its practical application to real chemical systems involves approximations to the exchange-correlation term in the Kohn-Sham Schrödinger equation.

Many exchange-correlation functional approximations have been developed, and it is well known that error cancellation among them greatly improves accuracy. The mechanism underlying these error cancellations remains unclear. Our new findings demonstrate the inherent correlation effects in exchange functionals in DFT using crucial quantum-chemical quantities, such as the correlated density and the correlation potential. We show that by tuning the difference between the Hartree-Fock and Semi-Local exchange in hybrid DFT, we can achieve significant improvements across diverse observables, including the electron self-interaction, a critical problem in DFT. Based on these, we developed a new global hybrid XC functional, named UMK26 (Uniwersytet Mikołaja Kopernika w Toruniu).

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Two microwave-shielded ultracold molecules in an optical tweezer

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Microwave shielding is a widely used and highly effective technique for realizing degenerate Fermi gases and Bose–Einstein condensates (BECs) of polar molecules. The resulting shielding potentials, which cannot be accurately described by simple contact models, feature large repulsive cores that successfully suppress collisional losses. Despite significant advances in understanding the many-body physics of these systems, the behavior of just two microwave-shielded polar molecules (MSPMs) confined within a single optical tweezer remains largely unexplored. In this work, we demonstrate that the shielding potential introduces interaction-dependent energy shifts comparable to the intrinsic energy-level spacing of the tweezer. We also present promising applications for pairs of confined MSPMs, including tetramer formation at efficiencies significantly higher than current realizations. Finally, we estimate the parameters required to realize a multichannel Hubbard model using MSPMs within a realistic optical lattice setup.

Single Molecule Detection in hBN Metasurfaces

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This study is devoted to the design of a complementary all-dielectric metasurface formed hexagonal Boron Nitride (hBN) film, including cylindrical cavities. The optical response sustains high-Q resonances in the visible regime and uniform electric field inside the cavities due to the quasi-bound states in continuum[1, 2]. We investigate the single-molecule detection process by considering a single rhodamine 6G molecule in ethanol solvent inside the cavity. The schematic of the hBN metasurface with a single molecule inside a cavity is shown in Fig.1(a). The signal-enhancement intensity of a single molecule is investigated with equation (1)[3]:

$$I_{SE} = \left| \frac{E(\mathbf{r}, \omega)}{E_0(\mathbf{r}, \omega)} \right|^2 \times F_p, \quad (1)$$

where $E(\mathbf{r}, \omega)$, and $E_0(\mathbf{r}, \omega)$ are electric fields in the molecule's position in hBN metasurface and free space, respectively. The F_p is the Purcell factor of a molecule inside the hBN cavity metasurface, defined as:

$$F_p = \frac{3}{4\pi^2} \left(\frac{\lambda}{n} \right)^3 \frac{Q}{V_{\text{eff}}}, \quad (2)$$

where λ is the free-space resonant wavelength, n is the refractive index of the medium, Q is the quality factor of the resonance and V_{eff} is the effective mode volume. The effective mode volume can be calculated by:

$$V_{\text{eff}} = \frac{\int_V \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2 dV}{\max[\epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r})|^2]} \quad (3)$$

The signal-enhancement intensity in the logarithmic scale is shown as a function of the cavity diameter in Fig.1(b), demonstrating strong intensity enhancement in larger volumes compared to traditional plasmonic cavities. The signal-enhancement intensity in the hBN cavity with a diameter of 70 nm with respect to free space is around 9 orders of magnitude.

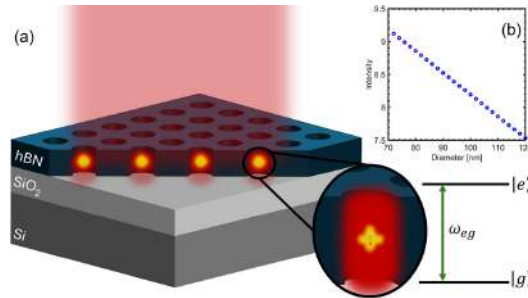


Figure 1: (a) hBN metasurface with a periodic array of cylindrical nanocavities, each hosting an rhodamine 6G molecule. (b) Signal-enhancement intensity of the hBN metasurface as a function of the cavity's diameter in logarithmic scale.

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Spin-boson models with competing interactions

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We apply hybrid variational framework to interacting spin-boson Hamiltonians that targets regimes where simulations are limited by the unbounded bosonic Hilbert space and strong many-body correlations. The bosonic sector and spin-boson correlations are captured within a compact non-Gaussian variational manifold, yielding an effective spin Hamiltonian that is solved with DMRG/MPS inside a self-consistent energy-minimization loop, without introducing an explicit photon-number cutoff in the many-body solver. We benchmark the method on the Dicke and Dicke-Ising models by comparison to converged spin-photon DMRG, finding accurate ground-state energies with reduced MPS bond dimensions. Applying the same workflow to extended Dicke models with more general direct interactions, we reproduce both standard phase transition scenarios and correlated regimes where mean-field treatment fails qualitatively.

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Neutral Atom Tweezer Array Quantum Computing at NQCC

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Neutral-atom tweezer-array quantum computing is a promising approach for scalable quantum computing, promising identical high-quality qubits, fast entanglement via Rydberg interactions [1], and long coherence times [2]. Recent experiments have demonstrated arrays containing thousands of atomic qubits, with gate fidelities above 99.5%, and sub-microsecond gate durations. Experimental implementations continue to evolve rapidly, incorporating developments in science, engineering, and quantum computing theory [2–5]. Single-species platforms based on Rb or Yb have achieved leading performance, typically relying on zonal architectures to reduce unwanted atom-light interactions. On the other hand, dual-species Rb-Cs systems exploit distinct transition wavelengths, simplifying mid-circuit ancilla measurement and coherent atom reloading, critical for scalable quantum computing.

Here, we present the development of a scalable, high-TRL, modular approach to neutral-atom quantum computing testbeds within the Tweezer Array Quantum Computing (TAQC) group. We follow open-source design principles and are guided by the need for regular subsystem upgrades to support systems engineering and rapid prototyping, test and integration.

The platform comprises modular cooling, trapping, imaging, laser addressing, and RF addressing systems. These are supported by a high-TRL, rack-mounted, modular laser delivery system that provides frequency stabilization, intensity control, laser safety, monitoring, and mechanical switching to enable rapid assembly and reconfiguration of a system for laser-based quantum control. Laser and EM subsystems are mechanically referenced to a commercially available vacuum system, providing stable quantum control. This modular design philosophy is further extended to the modular quantum processor unit (QPU), engineered to support both single- and dual-species (Rb-Cs). Real-time control is achieved through the open-source ARTIQ and Sinara platform.

This modular platform has allowed our team to rapidly demonstrate 2D and 3D MOT operation, as well as single-atom loading and imaging in optical tweezer arrays generated using spatial light modulators (SLMs). Our team is currently working to demonstrate laser-based single and two-qubit gate operation within our open, modular architecture, and to design the next generation of upgrades to the platform.

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Spontaneous symmetry breaking in nonlinear superradiance

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When atoms driven by classical fields emit harmonic photons into a quantum mode, the emitter inevitably changes its own state. Atoms and light become entangled. Still, in a typical experiment, this entanglement is hardly observable, as emitters become entangled with many photonic modes at once, obscuring entanglement between the emitter and any single mode.

In our work [1], we consider a system of many atoms placed in a cavity, which is far detuned from the atomic resonance. The cavity constrains the quantum modes into which the atoms are allowed to emit and with which they are allowed to interact. As such, the photons emitted by the atoms now maintain entanglement with the original emitters. This leads to the emergence of correlations between the atoms and the cavity photons.

Furthermore, the cavity is tuned to the second harmonic of the driver field. Symmetry rules prevent atoms from emitting photons at the cavity frequency. However, the addition of a small second-harmonic field would break this symmetry. In our setup, this second-harmonic field is given by vacuum fluctuations inevitably present in the cavity. The initial emission is triggered by these fluctuations, causing the system to emit some second-harmonic radiation, which now exerts symmetry-breaking recoil on the emitters. This recoil reinforces the initially small symmetry breaking, phase-locking all radiation emitted subsequently by the atoms to the initial vacuum fluctuation.

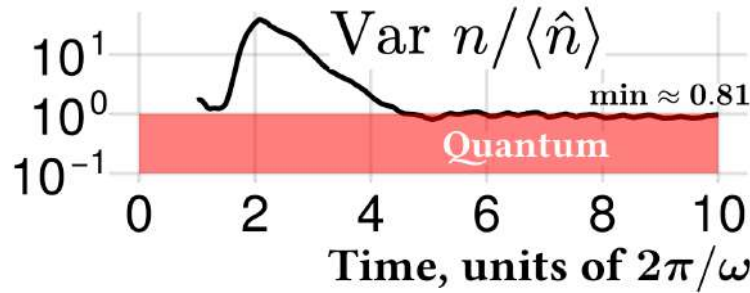


Figure 1: Photon dispersion relative to the total number of photons, plotted with respect to time measured in driving laser periods. Values below 1, marked in red, are prohibited for classical fields.

Consequently, the emitted field develops a nonclassical state with sub-Poissonian photon number dispersion, which is displayed in Figure 1. This state only emerges once the emitter atoms develop correlations with each other and the cavity photons. We thus demonstrate the first (to our knowledge) protocol for revealing quantum correlations between atoms by optical spectroscopy of the light they emit. We observe that these are accessible through the looking glass of quantum statistics measured for a light mode strongly coupled to collective dipole excitations.

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Optimization of two-photon absorption: Unidirectional photon pairs

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We consider an interaction of a three-level atom of a ladder configuration with a unidirectional propagating light prepared in a continuous-mode two-photon state [1]. We study the probability of two-photon absorption by the atom using the result obtained within the input-output formalism [2, 3] in the framework of standard assumptions made in quantum optics. Namely, a flat coupling constant, rotating wave approximation, and the extension of the lower limit of integration over frequency to minus infinity [2, 4]. Thus, we assume that the bandwidth of the light pulses is much smaller than their central frequencies. In this approach, the evolution of the atom interacting with a wave packet of a definite number of photons is given by a set of hierarchical equations [5, 6].

The starting point in our consideration is the analytical formula for the probability of two-photon absorption for the three-level atom. We study the time-dependent probability of the excitation of the system. In this work, we determined the optimal pulse shape for efficiently exciting the system to its final state and compared it with Gaussian pulses, which are more practical to generate in the laboratory. We also explore and show the differences between uncorrelated light and entangled photon pairs produced by spontaneous parametric down-conversion (SPDC). Our analysis showed that in the virtual state regime, where the intermediate state has a short lifetime compared to the final state lifetime, entangled pulses present a significant advantage for the excitation process. However, when the intermediate state has a longer lifetime, uncorrelated (separable) photons become more favorable. Furthermore, we compare the excitation dynamics driven by unidirectional photon pairs with those driven by bidirectional pairs and observe that unidirectional photons can significantly enhance the excitation probability in certain parameter regions.

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Sensitivity of neutron capture reaction rates to precise nuclear inputs

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It is known that very neutron rich nuclear isotopes in the low and medium mass region serve as stepping stones for the formation of heavy elements in the various astrophysical scenarios [1]. Along a given reaction network, these exotic nuclear structures play a critical role in determining the abundance of various isotopes, particularly for the neutron capture processes of nucleosynthesis, especially the r-process. The *rapid* neutron capture, or the r-process primarily takes place in extreme astrophysical environments, such as core-collapse supernovae and neutron star mergers and is responsible for most of the nuclei heavier than iron, away from the valley of stability. The efficiency of the r-process is heavily influenced by the structure of participating exotic nuclear systems [2]. Nevertheless, the lacunae in our knowledge database for nuclear attributes demand that exotic nuclei be studied systematically so that their properties, as inputs to reaction networks and abundance calculations, be known precisely.

With the theoretical framework of calculating reaction rates under the framework of the post form finite range distorted wave Born approximation (FRDWBA) theory of nuclear reactions [3], we will try and show the sensitivity of nucleosynthesis projections to nuclear structure inputs. It will be seen that capture cross-sections are highly sensitive to the structure information that goes in. Comparisons of JINA-REACLIB rates with FRDWBA rates will show that this sensitivity propagates to the reaction rate and abundance calculations, highlighting the requirement of using precise nuclear structure inputs for cross-section, reaction rate and isotopic abundance calculations.

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Nonlinear mixing of optical vortices to entangle photonic orbital angular momenta

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The optical vortex carries an orbital angular momentum (OAM), which is a quantum variable of the photon; this is particularly interesting because, in principle, it can take on all relative integer values.

Through nonlinear interaction, vortices can be combined to produce new, correlated vortices whose OAMs are entangled, or even multi-entangled. The specific nonlinear process employed and the class of vortices used determine the properties of the entangled OAMs, particularly those of OAM pairs in the case of a four-wave mixing.

We present a study which demonstrates the advantages of perfect vortices [1] over the usual Laguerre-Gauss modes in this context [2].

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EGAS 57

Tuesday Poster

Session

Tuesday, June 22rd 17:10-19:00

Storage-ring experiments with polycyclic aromatic hydrocarbon ions

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Polycyclic Aromatic Hydrocarbons are believed to be highly abundant in the interstellar medium [1] and therefore it is of significant interest to study the stability of these molecules, their ions, derivatives and fragments, as well of their collisions at low energies with other species abundant in this environment.

The Double ElectroStatic Ion-Ring ExpEriment, DESIREE [2], at Stockholm University offers unique conditions for studying PAH ions in isolation and in collisions. This poster will be presenting an overview of the experimental results of experiments with PAHs conducted so far. These will include studies of the stability of fragments of coronene ($C_{24}H_{12}$) ions having lost a single carbon atom in a knock-out collision [3], and of the stability of ions of cyano-naphtalene [4] – the first PAH specifically identified in space [5].

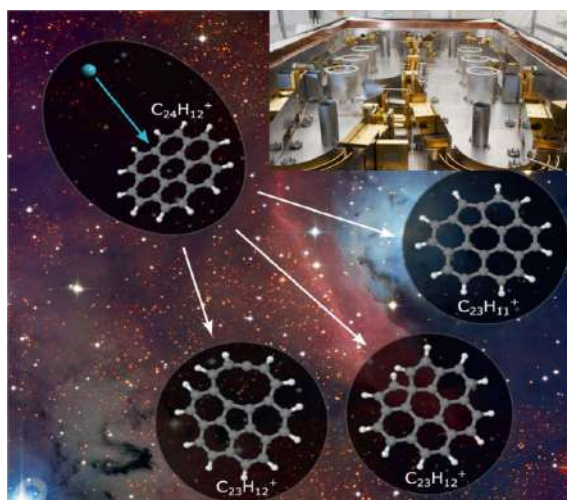


Figure 1: Coronene fragment ions after collisions at typical stellar wind velocities with helium atoms shown on an ISM background. The inset is a photograph of the inside of DESIREE taken during an opening.

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Neutral, cationic, and anionic alkali-metal and alkaline-earth-metal monohydrides: Interaction potentials, dipole moments, and rovibrational structure

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Simple diatomic molecules play an important role in quantum chemistry and physics by providing the playground for benchmarking molecular theory and implementing quantum control. Precise calculations of molecular properties are crucial for guiding ongoing experiments and for planning new ones. Ultracold molecules provide a good framework for observations of quantum effects and testing various theories. Alkaline-earth-metal monohydrides are also promising candidates for a source of ultracold hydrogen [1] and laser cooling to ultralow temperatures [2].

Calculations of potential energy curves are a groundwork for determining other molecule properties such as rovibrational states. Neutral alkali and alkaline-earth monohydrides have already been extensively studied by others [3], unlike their ions. Experimental spectroscopic studies on the BaH^{2+} molecule are currently underway in Prof. F. Merkt's group at ETH Zurich, where recently BaH^+ and BaD^+ were studied [4]. Here, we aim to provide the interaction energies for all neutral and ionic alkali and alkaline-earth hydrides as accurately as possible using various methods and basis sets.

We applied coupled cluster theory (CCSD, CCSD(T), CCSDT and MRCCSD) for post-Hartree-Fock calculations. A range of different electronic structure techniques was employed to achieve a high level of accuracy and provide insightful comparisons. Basis sets with cardinal numbers up to 5Z were utilized and the energies were extrapolated to the complete basis set limit. We applied corrections such as the diagonal Born-Oppenheimer correction (DBOC) and the correction for the full triple excitations in the coupled cluster calculations. Potential energy curves were calculated for distances ranging from $2 a_0$ up to $50 a_0$. Adopted corrections helped us improve the precision of our results and allowed us to reach a theoretical accuracy of around 0.5% - 1.5% at the minimum.

The results of our calculations serve as a strong foundation for deriving other molecular parameters. The ionized alkali and alkaline-earth hydrides have not been extensively studied by others in terms of *ab initio* calculations and our results are among the most accurate available. Additionally, they provide a valuable reference for comparison with experimental data.

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Laser slowing and cooling of aluminium monofluoride

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In recent years, ultracold molecules have become a very promising platform for quantum information processing, studying quantum many-body physics and testing new physics beyond the Standard Model of particle physics. Among molecules where trapping has been demonstrated aluminium monofluoride (AlF) is unique due to its structure which is analogous to alkaline earth (like) atoms (Yb, Sr, Cd). This enable high capture rates from a strong dipole-allowed transition (near 227.5 nm) and the possibility of using a spin-forbidden narrow-line transition to cool to temperatures in the μK range.

This work presents progress on developing high-powered, VECSEL-based laser systems in the deep-ultraviolet. We also show results in slowing AlF, both from experiment and simulations. Simulations pertaining to the properties of both red- and blue-detuned AlF MOTs are also presented, focusing on reducing temperature and size, which is an essential step before loading into a dipole-trap. These techniques are of importance due to the recent progress in the capture and trapping of AlF in a red-detuned trap [1].

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Measurement of the lifetime of the metastable $5d\ ^2D_{3/2}$ level of Ba^+

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The Ba^+ ion has a simple electronic structure with a single electron outside a xenon-like core. Due to the significant core-penetration of low- l electrons, the $6s$ level is lower in energy than $5d$. This leads to the energy-level structure in Figure 1, with the ground state being $6s\ ^2S_{1/2}$, and the first excited levels being the two fine structure levels of the d -state: $5d\ ^2D_{3/2}$ and $5d\ ^2D_{5/2}$. These are metastable as they have the same parity as the ground state such that electric-dipole transitions are forbidden. We measure the lifetime of the metastable $5d\ ^2D_{5/2}$ level.

The experiment is performed by storing a beam of Ba^+ ions at 10 keV in the cryogenic DESIREE storage-ring [1]. By optical pumping, all population in the ground state is transferred to the metastable $^2D_{5/2}$ level. After the pumping, the population is probed as function of time by exciting the remaining ions in the $^2D_{5/2}$ level and detecting the fluorescence. The excellent vacuum of the storage-ring allows for storage of the ions on much longer time scales than the intrinsic lifetime measured to be 82.9 ± 1.4 s (after preliminary analysis – final result should have smaller uncertainty). The essentially collision-free environment allows for an essentially correction-free measurement with the only non-controlled systematic effect is a small population in $5d\ ^2D_{3/2}$ level, which disturbs the normalization measurement when decaying to the ground state.

Our result is more precise than – and consistent with – those of earlier measurements of this lifetime in a room-temperature storage ring [2] and in an ion trap [3] using similar optical pumping schemes.

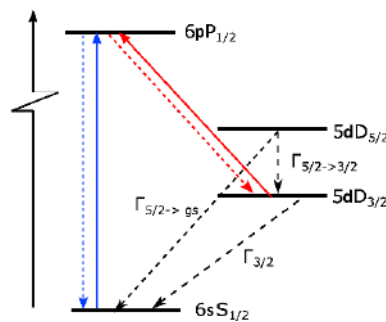


Figure 1: Relevant energy levels of the Ba^+ ion. By the blue ‘pump’ laser (493 nm) the ion population is transferred to the $5d\ ^2D_{3/2}$ level. The population of that level is measured on a relative scale as a function of time by applying the red ‘probe’ laser (650 nm) and observing the blue fluorescence.

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Initial-state control in mutual neutralization of Si^- with Na^+ or K^+ revealing strong violations of Wigner's spin-conservation rule

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Mutual neutralization (MN) is a fundamental electron-transfer process in which oppositely charged ions collide to form neutral products. Using the Double ElectroStatic Ion Ring Experiment (DESIREE) facility at Stockholm University [1], we investigated low-energy MN collisions between state-selected Si^- ions and Na^+/K^+ ions [2]. By applying state-selective laser photodetachment, metastable $\text{Si}^-(^2\text{D})$ ions were removed, enabling measurements with pure ground-state $\text{Si}^-(^4\text{S})$ beams as illustrated in Fig. 1. The experiments revealed neutral Si products in the excited ^1D and ^1S states, providing direct evidence for MN channels that break Wigner's spin-conservation rule (the total spin is $3/2$ in the initial state and $1/2$ in the final state) [3]. These results demonstrate the importance of initial-state control in collision experiments and indicate that spin-forbidden reactions can contribute to MN cross sections at sub-eV collision energies.

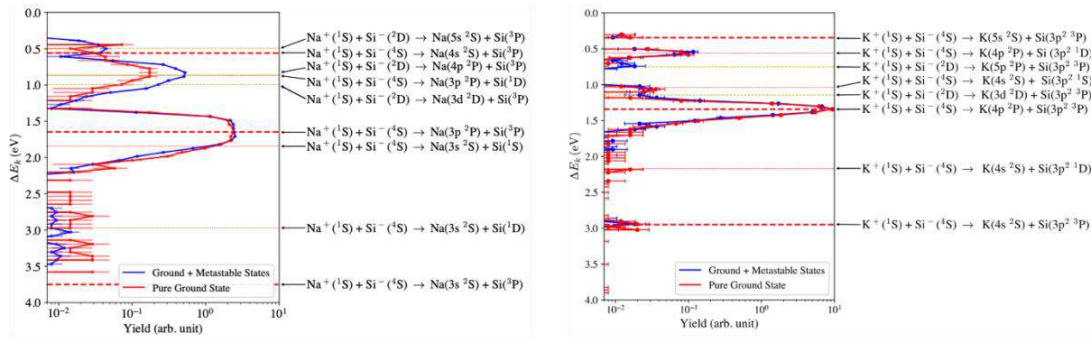


Figure 1: Kinetic energy release (ΔE_k) distributions for mixed-state (blue) and pure ground-state (red) anion beams. Horizontal dashed lines denote the expected ΔE_k values: red lines represent channels accessible when Si^- is in the ground state, while yellow dashed lines indicate contributions from the metastable $\text{Si}^-(^2\text{D})$. Among the red dashed lines, long red dashes correspond to neutral silicon formed in the ^3P ground term, whereas short red dashes indicate channels producing Si in the excited ^1D and ^1S terms

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High-resolution laser photodetachment spectroscopy of Na^-

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The electron affinity (EA) of sodium is of particular interest because it is one of the most cited EAs due to its importance in chemistry. However, the most precise EA mentioned in the literature is from a review from 1985 [1], where the value is based on an unpublished paper. This motivates a new experimental determination of the EA of sodium with high resolution.

In this work, we present a new study of the EA value of Na. We have performed a photodetachment study by measuring the threshold for the process $\text{Na}^-(3s^2, ^1S_0) + h\nu \rightarrow \text{Na}(3s, ^2S_{1/2}) + e^-$, where the outgoing electron is a p -wave giving a slow onset of the threshold and hence a low resolution EA determination. We thereafter aim to study the onset of the excited state channel $\text{Na}^- + h\nu \rightarrow \text{Na}(3p) + e^-$, where the emitted electron has an s -wave character, giving a sharp onset at the photodetachment process [2], which will allow a high resolution EA determination. In the experiment, a negative ion beam is produced in an ion-beam sputtering source and accelerated to a kinetic energy of 6 keV. The Na^- beam is selected with a mass-separating magnet and steered with a quadrupole deflector into the interaction area where it interacts with one or two laserbeams. The different beam components are separated by their charge after the interaction region. The Na^- ions are deflected into a Faraday cup, while the produced Na^+ ions are guided towards a microchannel plate (MCP) detector, which records both their impact position and arrival time. Neutral sodium atoms are not affected by the electric fields of the analyzer and therefore continue in a straight trajectory to a neutral particle detector (NPD) [3]. This detection scheme allows charged and neutral particles to be measured separately, reducing background contributions and improving the selectivity of the experiment. The experiment leaving the residual atoms in the groundstate was performed with a single laserbeam working in the infrared laser. The yield of atoms produced in the photodetachment process was measured with the NPD, and the onset of the process was determined. In the forthcoming experiment we will use two laser beams. The first laser with wavelength λ_1 will photodetach the Na^- ions leaving the sodium atoms in the $3p$ state. After a delay of a few ns, the second laser pulse, with wavelength λ_2 , photoionizes the neutral $\text{Na}(3p)$ atoms, producing Na^+ ions which will be recorded with the MCP. By scanning the photon energy of the photodetachment laser across the threshold region, the onset of the photodetachment signal can be measured and fitted using the Wigner law. This approach has been shown to be an effective method for high-resolution measurements of electron affinities [4].

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Caesium photoionization for monochromatic electrons source for surface electron microscopy

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By combining a monochromatic electron source based on the ionization of Rydberg atoms with high-performance time and position detectors, we are developing, in collaboration with ISMO and SPEC, a novel electron microscope called HREELM. This microscope enables full-field imaging with a spatial resolution of 10 nm and the analysis of vibrational interactions on surfaces with a spectral resolution of 10 meV. Potential applications span nanophysics, nanochemistry, and photonics.

We are specifically developing a monochromatic electron source based on the excitation and ionization of cesium atoms in Rydberg states, achieved through a combination of lasers and an electric field. The low energy dispersion necessitates a careful selection of the excited Rydberg state under a weak electric field, as described by the formula $\Delta E = F\Delta z$. Additionally, we employ an original electron energy loss measurement scheme based on ion-electron correlation.

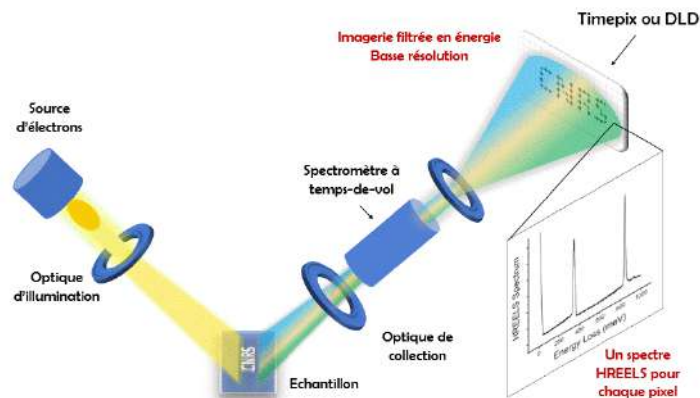


Figure 1: Diagram showing how HREELM works, with electron pulses arriving on the sample and then being detected by Timepix, enabling both imaging and energy measurement.

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Multi-laser stabilization system for ultracold-Rydberg-atom and precision-spectroscopy experiments

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Ultracold-Rydberg-atom and precision-spectroscopy experiments often require multiple lasers that need to be frequency stabilized to reach the desired precision and efficiency of these types of experiments. The cost and complexity of the equipment needed for the different laser stabilization techniques in these multi-laser setups can ramp up quite fast. Multiple open-source FPGA development boards from Red Pitaya together with a modified open-source lockbox software package called PyRPL [1] are used to design a laser stabilization system based on Fabry-Pérot (FP) cavities that can implement different stabilization techniques in a compact, scalable and cost-efficient way.

I will describe the architecture of the system implemented in our lab to stabilize up to nine lasers simultaneously. The setup relies on the transfer of the stability of lasers locked to atomic references (Rb, Cs, Ca) to other lasers operated at different frequencies using FP cavities. This stability transfer is done with two techniques: scanning transfer cavity locking [2] and the Pound-Drever-Hall technique [3]. In each stabilization technique, the Red Pitaya plays a central role in the stabilization feedback loop: generating the error signals and modulation signals and driving the piezoelectric actuators of the FP cavities. Additionally, frequency-modulation-based laser locking is implemented using an acousto-optic modulator (AOM) for frequency modulation instead of the usual electro-optic modulators (EOMs) or modulation of the laser current/piezo voltage. The multi-laser stabilization system based on the open-source Red Pitaya boards can easily be adapted to match the specific needs of an experiment while being compact and cost-efficient.

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Collective early-time spontaneous decay of a strongly driven cold atomic cloud

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The laser cooling theory developed and implemented since the end of the last century has opened the door to a whole new field of physics, so-called Cold Atoms ([1], [2] and [3]). In this spirit, one of the tools that has been developed is the magnet-optical trap (MOT), where in addition to the laser cooling, one can apply a magnetic field gradient to trap cooled atoms, to form a cold atomic cloud.

One can use these trapped atoms to investigate light itself, more specifically how it scatters from these atoms. One of the advantages is the capability to control characteristics of the atoms, such as the cloud density, optical density (OD), temperature etc. Moreover, interesting effects arise when the atoms are brought closer together (thus increasing the OD), transitioning from independent to collective behavior ([4] and [5]). When the atomic cloud is sufficiently optically dense, the natural lifetime of spontaneous emission can be modified: it may become longer or shorter, corresponding to subradiant and superradiant regimes, respectively.

We present here [6] a numerical and experimental investigation of the collect decay of a dilute cloud of approximately 10^8 atoms by varying the Rabi frequency (Ω) of the drive. We examine the transition from weak to strong driven regime for angular-dependent (scattered light from the cloud) and also for a global (excited state population) observable. Simulations and experiments show that on resonance, by scanning the driving parameter, a transition from subradiance to superradiance occurs for the angular-dependent quantities followed by a suppression of this latest regime, whereas for the global quantities the transition goes from subradiant to single emitter behaviour.

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Dissipative spin manipulation in a SU(N) symmetric Fermi gas

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Strontium-87 is an alkaline-earth atom with a nuclear spin of $I=9/2$ that exhibits SU(N) symmetric spin interactions. This type of interaction leads to exotic physics in strongly correlated, interacting systems. Interesting quantum states require correlations between atoms, and the Hamiltonian-dynamics approaches used to generate them are challenging to implement because of the stringent requirements on losses and entropy. An alternative approach is to use dissipation techniques to favor spin correlations.

The idea that we follow is to induce spin-selective two-body losses using a photoassociation laser [1], [2]. The two-body losses will be spin-selective due to Pauli's exclusion principle, and only pairs of atoms in a singlet spin state will be affected. The remaining atoms will qualitatively align their spins along the same axis, driving the system into a fully symmetric Dicke states. These states are highly sensitive to phase changes and have a great metrological interest.

To fully characterize such large collective spins in an alkaline-earth ensemble ($I = 9/2$), for which projection measurements along (x, y, z) are insufficient, we have developed a method to coherently manipulate the spins throughout their wide Hilbert space and implement complete measurement sets [3].

Here, I will present the first observation of photoassociation lines on the $^1S_0 - ^3P_1$ transition of ^{87}Sr , calibrated through prior experiments on ^{88}Sr . We show that the measured line positions and characteristic disagree with our current theoretical predictions. Building on this, we intend to create correlated states with and without a lattice and characterize their spin fluctuations, correlations, and metrological interest [4].

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A new interconnection platform for neutral atom arrays

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Advances in the manipulation of arrays of individual Rydberg atoms have demonstrated the potential of the latter for quantum information [1]. However, actual applications in quantum computing will require millions of logical qubits, themselves encoded on tens of single atoms. The number of atoms in a single array will reach a limit (on the order of 10^4), defined by the available laser power, the field of view offered by high-NA optics or the resolution of spatial light modulators defining the geometry of the array. This limit calls for the development of distributed quantum processing, which requires quantum interconnections. Our proposal for this necessary development is a platform that will allow the connection of atomic processors through an intracavity Rydberg superatom.

By coupling an atomic cloud to a medium-finesse cavity and driving it to a highly excited state, we can achieve a collective two-level system called a superatom [2]. The main advantage of such a platform is that the collective coupling of the atomic cloud to the cavity bypasses the challenges for a high-finesse cavity and the high sensitivity of Rydberg atoms to nearby dielectric surfaces. In our group, the coherent mapping of the state of the superatom onto a free-propagating photonic qubit has been demonstrated [3].

Building on this scheme, we propose trapping an array of atoms, via optical tweezers, next to the atomic cloud within the cavity mode. The aim is to entangle the individual atom with the superatom, then map the superatom onto a free-propagating light mode. This will result in an entangled single-atom single-photon state, forming a building block to distribute entanglement between distant single-atom arrays.

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Progress in Optical Dipole Trap Towards Photo-Association Spectroscopy

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The experimental setup based on a single-beam optical dipole trap (ODT) for cold Hg atoms enables the investigation of new hadron-hadron interactions [1] through photo-association(PA) spectra [2] near dissociation limit. Mercury atoms forming Hg_2 , one of the heaviest two-atom molecules, are well-suited for this experiment. The Hg-Hg Van der Waals interaction is well characterized [3] and significantly weaker than in Sr_2 or Yb_2 , reducing interatomic effects enhanced sensitivity to explore new physics beyond the Standard Model at nanometer scale.

For the first time, we have achieved Hg ODT, which represents the least polarizable atoms trapped to date, with temperatures reaching the microkelvin range. The ODT significantly enhances the atomic cloud density which is crucial for PA experiment. Experimental results, including the loading dynamics of the ODT, measurements of trap lifetime, determination of trap frequencies, overall performance of the trapping system, and the experimental scheme for PA experiments will be presented.

The experiment will be carried out using the dual-species experimental setup [5]. PA resonances can also be regarded as optical Feshbach resonances, which serve as a powerful tool for controlling atomic interactions [6]. The Hg_2 molecules will also be employed to investigate the potential for the realization of an optical molecular clock [7, 8].

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Ultraprecise determination of quantum defects and ionization energy of the cesium atom

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Accurate knowledge of atomic structure enables the engineering of atomic properties. Recent advances in quantum technologies, including Rydberg-atom-based electric field sensors and neutral-atom-based quantum computing, have made the detailed characterization of highly excited states increasingly important for both fundamental studies and practical applications. We present ultraprecise absolute-frequency measurements for Cs transitions from the $|6S_{1/2}, F = 3\rangle$ hyperfine ground state to the $nS_{1/2}$ ($n = 23\text{--}90$), nD_J ($n = 21\text{--}90$), and nF_J ($n = 28\text{--}68$) Rydberg states with an accuracy of less than 72 kHz [1, 2]. Atomic spectra are obtained using two- and three-photon excitation schemes referenced to an optical frequency comb in a sample of ultracold ^{133}Cs . By globally fitting the experimental data to the modified Ritz formula, we determine the most accurate quantum defects to date of the $nS_{1/2}$, $nD_{3/2}$, $nD_{5/2}$, $nF_{5/2}$, and $nF_{7/2}$ series [1, 2] and report a new ionization energy of $31\,406.467\,751\,48(14)\,\text{cm}^{-1}$ [1]. The uncertainty of the obtained ionization energy is reduced by an order of magnitude with respect to the best previously available result [3]. Based on improved wave functions determined for the new quantum defect energies, we calculate the reduced electric-dipole matrix elements. The results are found to be in accordance, within theoretical uncertainties, with high-level relativistic many-body calculations of Safronova et al. [4] for low excited states, to which our measurements are extrapolated. We also calculate and parameterize the fine-structure splittings and quantitatively evaluate core contributions.

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When probing Balmer transitions reveals low-energy ion-atom collision dynamics

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When a slow ($\sim \text{keV/u}$), highly charged ions (HCI) collides with an atom, one (or several) electrons could be captured in highly excited states (e.g., $n_c = 9$ for Ar^{16+} on N). These very excited states rapidly decay via a complex electronic cascade process, that finally ends with X-ray emission. In the case of Ar^{q+} ($q=9-16$), X_L spectroscopy (transitions to $n = 2$) gives information on the number of electrons populating the M shell at the end of the cascade. These Balmer transitions have already been studied in ion-matter interaction [1], but several uncertainties on spectroscopic assignment remain.

Balmer transitions of Ar^{q+} ions with charge states $q = 9-16$ were recorded (Fig. 1) using a semiconductor detector equipped with a polymer window, providing both high energy resolution (60 eV @ 500 eV) and high detection efficiency (0.4 @ 500 eV). Relativistic Multi-Configuration Hartree-Fock (MCDHF) calculations [2] for $n = 3 \rightarrow 2$ transitions enable decomposition of the main experimental peak. In addition, screened hydrogenic calculations [3] allow assignment of peaks from the Paschen series (transitions to $n = 3$) and the Balmer series limit (e.g., Ar^{13+} in Fig. 1). The emission is attributed to two dominant contributions: primarily $3d \rightarrow 2p$ transitions for Ar^{q+} ($q \geq 12$) and $3s \rightarrow 2p$ transitions for Ar^{q+} ($q \leq 12$). MCDHF fluorescence yields, combined with experimental intensities, provide access to the relative population of the $n = 3$ subshells (Fig. 2).

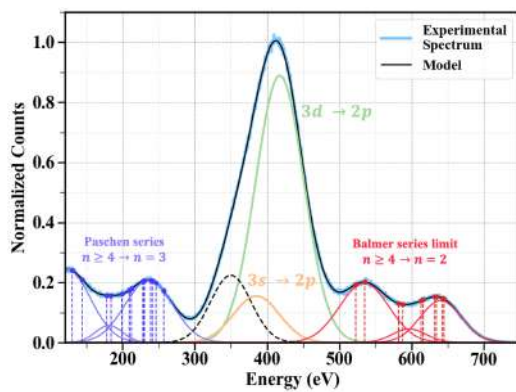


Figure 1: Spectral decomposition of X_L transitions from Ar^{13+} -atom collisions.

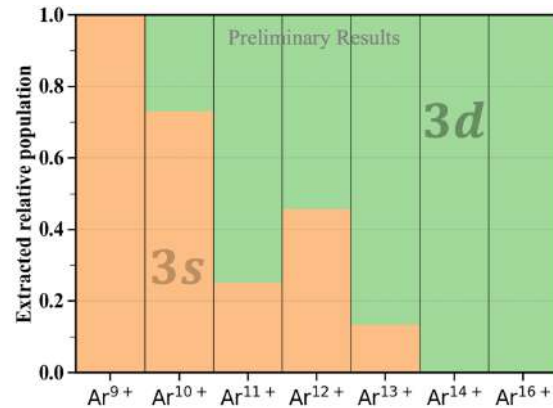


Figure 2: Relative populations extracted from X-ray spectra of $n=3$ shell for Ar^{q+} ions ($q = 9-16$).

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Strongly dipolar alkali-metal–silver molecules: Electronic structure and spectroscopic properties

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Ultracold polar molecules are an ideal platform for exploring fundamental questions in quantum physics and chemistry. Strong, long-range, and anisotropic dipolar interactions play a central role in all such molecular implementations, making the permanent electric dipole moment (PEDM), d , a key figure of merit for ultracold molecules. Recently, it was predicted that ground-state alkali-metal–silver molecules should have dipole moments twice those of the most dipole alkali-metal ones, resulting in four times stronger dipolar interactions ($\sim d^2$) [1]. Deep ground-state potentials provide the opportunity to use shorter-wavelength laser fields for optical lattices and tweezers without photoinduced losses and with even twice smaller distances, R , between trapped molecules, resulting in an additional eight-fold increase of dipolar interaction strengths ($\sim 1/R^3$). Thus, at least 32 times stronger intermolecular dipolar interactions and 32 times faster dynamics can be realized with alkali-metal–silver molecules compared with those with the most dipolar alkali-metal molecules.

In this study we present a systematic theoretical study of the ground and lowest excited states properties of highly polar diatomic molecules consisting of a silver atom interacting with an alkali-metal (Li, Na, K, Rb, Cs, and Fr) one. We employed state-of-the-art *ab initio* electronic structure relativistic coupled cluster method with large Gaussian basis sets and small-core relativistic pseudopotentials to account for the scalar and vector relativistic effects. We calculated potential energy curves (Figure 1), PEDMs, spectroscopic parameters, and radiative properties including Franck-Condon factors and lifetimes. We confirmed that the studied molecules in their ground electronic states are strongly bound and exhibit highly polarized bonds, resulting in PEDMs that are substantially larger than those of heteronuclear alkali-metal dimers.

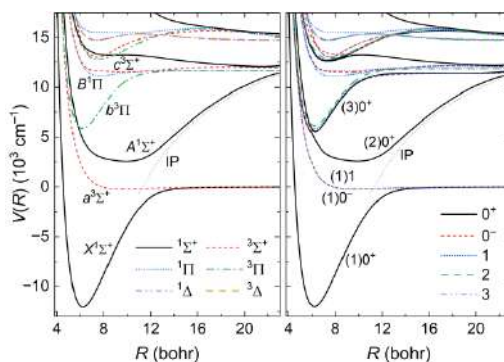


Figure 1: Potential energy curves of the ground and excited electronic states of the CsAg molecule without (left panel) and with (right panel) spin-orbit coupling.

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From Scale Invariance to Universal Droplets: Generalised GPE for Attractive 2D Bose Gases

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Dilute two-dimensional (2D) gases exhibit scale-invariant behaviour that is absent in their three-dimensional counterparts. In attractive systems, this symmetry can be strongly broken — a phenomenon known as the quantum anomaly — by the presence of universal many-body bound states (droplets). To explore this anomaly, especially the corresponding time dynamics, a simple yet powerful theoretical tool is required.

In this work [1], we introduce a density-dependent coupling into the Gross-Pitaevskii equation (GPE), which not only captures the quantum anomaly but also retains a structure suitable for both intuitive analytical and numerical analysis. In my talk, I will demonstrate how this approach naturally bridges the physics of trapped systems and self-bound droplets, and how it enables the investigation of excited states and complex collective dynamics.

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Collective inhibition of light scattering from atoms into an optical cavity at a magic frequency

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We report on the observation of a new magic frequency within the hyperfine structure of the D2 line of ^{87}Rb atoms at which light scattering into a high-finesse optical cavity [1] is strongly suppressed by the interplay of quantum interference and strong collective atom-cavity coupling. Polarization-resolved measurements of the cavity output reveal that both the Rayleigh and Raman scattering channels are extinguished at a detuning of about 185 MHz below the $F=2 \leftrightarrow F'=3$ transition (figure 1).

The coincidence of the dips in the two orthogonal cavity polarizations, together with their spectral shape, indicates that the effect cannot be understood within a single-atom scattering picture. Instead, it points to destructive interference in the polariton excitations of the strongly coupled atom-photon system. We also confirm the previously known magic frequency near -506 MHz, where only Raman scattering is suppressed by single-atom interference.

As a complementary cold-atom control technique, we have also developed the cold-atom buoy, a differential measurement scheme in a quadrupole trap, where reversing the trap polarity enables common-mode rejection in magnetic-field sensing based on atomic cloud displacement [3].

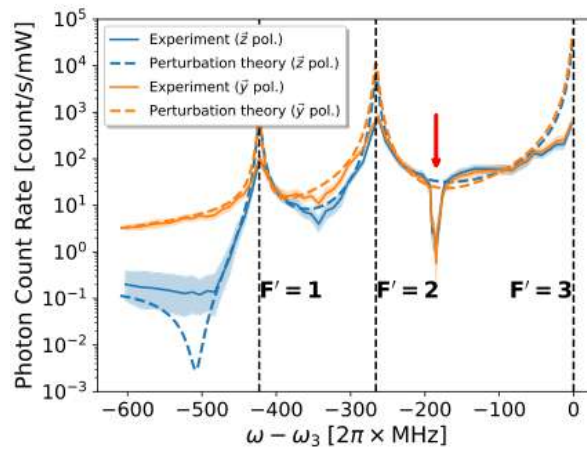


Figure 1: Polarization-resolved spectrum; the arrow marks the collective inhibition dip near -185 MHz [2]

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Towards studying ultracold ion-molecule reactions in supersonic beams

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Ion-molecule reactions (IMRs) can proceed with high rate coefficients even in the limit of absolute zero temperature. This makes them a key driving mechanism of astrochemistry [1] and an ideal testbed to probe quantum effects in cold and ultracold reactive collisions in the laboratory. Until recently, experimental studies of IMRs below ~ 10 K, and particularly near the ultracold (< 1 mK) regime, have been near impossible due to ion-heating by stray electric fields for free ions, or micromotion in the case of ions in traps.

We report on progress towards building an experimental setup to study quantum scattering effects in the $\text{He}^+ + \text{N}_2$ reaction [2], in the $E_{\text{coll}}/k_B \sim 1 \text{ mK} - 0.5 \text{ K}$ collision energy range. In the first experimental stage, we plan on exploiting intrabeam collisions between particles generated within a single pulsed supersonic beam. To reach these low energies, we make use of two experimental approaches: (i) the He^+ ion is substituted by a helium atom excited to a Rydberg state [$\text{He}(n)$, where n is the principal quantum number] in order to avoid heating from stray electric fields [3,4], and (ii) frequency-chirped laser light, counter-propagating the supersonic beam, is used to laser cool and slow the helium atoms and tune the $\text{He}-\text{N}_2$ relative velocities, and thus the collision energy ($E_{\text{coll}} = \mu_{\text{He}^+-\text{N}_2} |\vec{v}_{\text{He}^+} - \vec{v}_{\text{N}_2}|^2/2 = \mu_{\text{He}^+-\text{N}_2} |\vec{v}_{\text{rel}}|^2/2$).

We present our first experimental measurements of a cold dense supersonic beam of helium atoms in the metastable $(1s)(2s) \text{ } ^3\text{S}_1$ state (referred to as He^*), produced by thin-needle electric discharge at the orifice of a short-pulse valve. We also present the results of a particle-trajectory Monte Carlo simulation demonstrating the capability of laser-cooling light, resonant with the $(1s)(2s) \text{ } ^3\text{S}_1 \rightarrow (1s)(3p) \text{ } ^3\text{P}_2$ transition in He at 1083 nm and counterpropagating to the atomic beam, to decelerate the He^* atoms and significantly compress their phase-space distribution, enabling the ultracold collision regime.

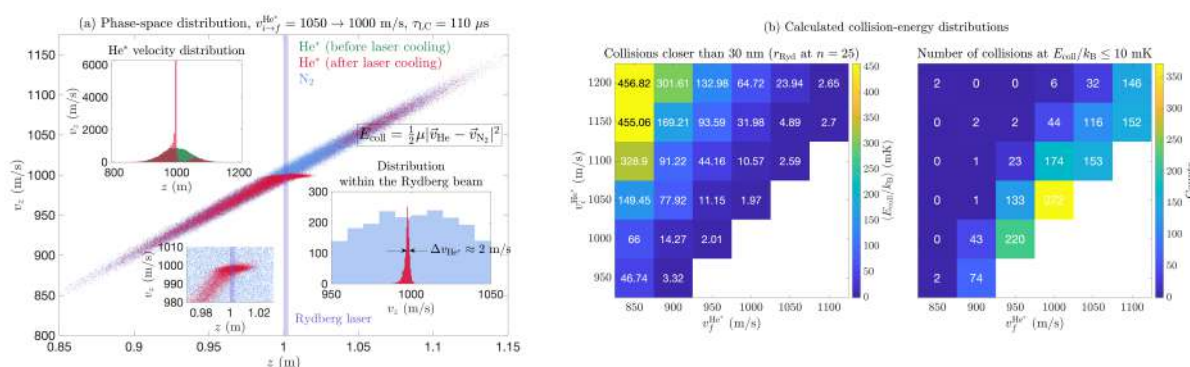


Figure 1: The results of the Monte Carlo simulation. (a) The effect of chirped laser cooling and slowing on the He^* supersonic beam. (b) Calculated collision-energy distributions for various initial (target) and final He^* velocities.

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Precision laser spectroscopy of trapped $^{173}\text{Yb}^+$ ions using a bath of ultracold atoms

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Systems combining laser-cooled trapped ions and ultracold atoms have been realized in different experimental setups over the last two decades. Reaching collision energies in the $10\ \mu\text{K}$ regime, the trapped ion-atom mixture can be used to resolve the spin dynamics of colliding particles. This allows quantum state preparation at the level of individual hyperfine and Zeeman states, with applications in precision spectroscopy and clocks [1].

In this work, we demonstrate laser spectroscopy of a trapped $^{173}\text{Yb}^+$ ion immersed in a bath of ultracold ^6Li atoms by observing the $^2S_{1/2} \rightarrow ^2P_{3/2}$ (D2) transition. We probe the transition with a 329 nm pulse sequence, after which the ion has a considerable probability of ending up in one of the metastable states $^2D_{3/2}$ or $^2D_{5/2}$ and subsequently decaying to the extremely long-lived $^2F_{7/2}$ state (see Fig. 1). During this time, there is a high probability of a collision with a ^6Li atom and charge transfer, resulting in ion loss [2]. The time between pulses was set to allow the ion to be cooled back to the $F = 3$ ground state via a spin-exchange collision with a ^6Li atom. In this way, spin-exchange collisions between the ion and the atoms continuously prepare the ground hyperfine level of the ion, while we use state-selective charge exchange to detect laser scattering as a function of frequency. We find the magnetic and electric hyperfine interaction constants for the $6^2P_{3/2}$ state to be $A = -241(1)\ \text{MHz}$ and $B = 1460(8)\ \text{MHz}$, respectively. Our results are in agreement with a previous measurement but are a factor of 6–9 more precise. The techniques demonstrated in this work may be extended to perform precision spectroscopy on other ions with complex level structures.

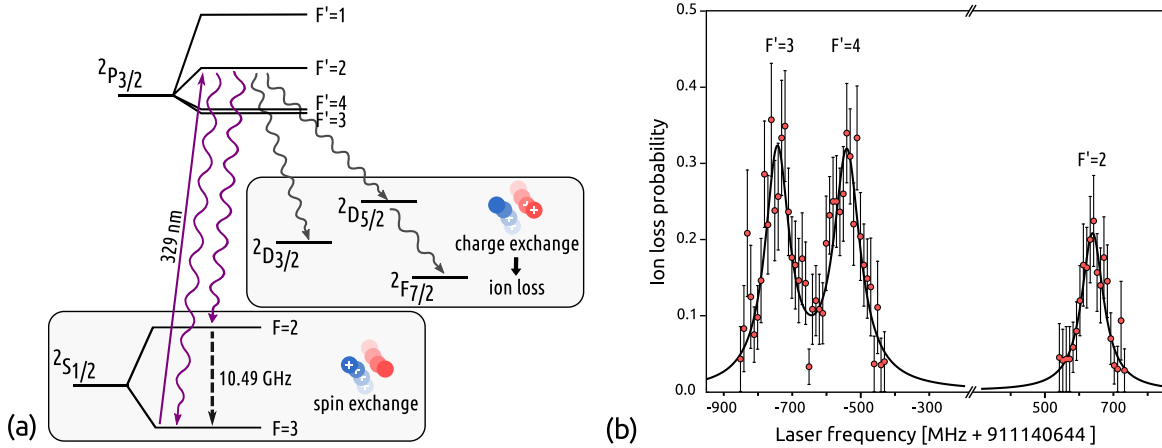


Figure 1: (a) Energy levels and relevant transitions in $^{173}\text{Yb}^+$ (not to scale). (b) The ion-loss spectrum of $^2S_{1/2} \rightarrow ^2P_{3/2}$ transition in $^{173}\text{Yb}^+$ from $F = 3$ to $F' = \{2, 3, 4\}$. The data is fitted by a sum of Lorentzian functions.

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High accuracy calibrations of the International Atomic Time with a Sr optical lattice clock

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In optical clocks, a narrow optical transitions in trapped ions or ultra cold atoms in a lattice is used at a frequency reference. They now surpass the cesium fountain clocks by two orders of magnitude, such that a redefinition of the SI second is envisioned in the next decade, replacing the cesium hyper-fine transition with one or several optical transitions [1]. The roadmap towards this redefinition [2] sets quantitative criteria optical have to fulfill. In particular, optical clock should demonstrate their ability to perform calibrations of the International Atomic Time (TAI).

The first calibrations of TAI by optical frequency standards date back to 2014, with the first steering calibrations in 2019 [3]. Since then, 11 optical frequency standards have produced calibrations of TAI, especially between 2021 and 2023. However, several shortcomings of these calibrations were identified:

- A significant decrease in the number of calibrations in 2024 highlights that maintaining an optical frequency standard over extended time intervals remains an operational challenge, especially in the context of arbitration between long-term metrological measurements and the research activities aimed at improving the performances of these standards.
- Only a handful of calibrations have reached a total uncertainty approaching the target uncertainty of 2×10^{-16} for the redefinition of the SI second. The uncertainty of past calibrations were hindered by a limited up-time, sporadic operation, or contributions with optical standards with larger uncertainty.

In this paper, we report on the operation of the LNE-OP SrB Sr optical lattice clock since April 2025, resulting, at the time of writing into 12 consecutive months of calibrations included in the BIPM Circular T. The up-time of these calibrations averages to 67% over this period, resulting in a dead-time uncertainty ranging from 0.5×10^{-16} to 1.2×10^{-16} . Combined with the clock systematic uncertainty of 4.6×10^{-17} , all these calibrations have an uncertainty lower than the 2×10^{-16} mark, which constitutes a significant progress in completing the roadmap towards the redefinition of the SI second. We will describe the improvements in the automation of the clock operation and of the systematic evaluation that enabled these contributions, and discuss perspectives for continued future calibrations.

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Modeling of superradiance in color centers in diamond in the theory of quantum open systems

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The remarkable properties of nitrogen-vacancy (NV) color centers in diamonds are expanding the horizons of contemporary quantum optics, opening the way to the development of, among others, quantum memories [1] and biomedical imaging [2]. An equally interesting phenomenon is superradiance, first described by R. H. Dicke in 1953 [3]. Today, superradiance is considered in many different variants and, thanks to its connection with single-photon emission [4], is becoming a phenomenon with significant application potential in quantum technologies. Importantly, according to some research groups [5], it may be possible to observe superradiance in color centers in diamonds, which could open new possibilities both for research in fundamental physics and for the search for technological applications. As part of our research, we developed a theoretical model of interactions for systems of this type [6]. Its purpose is to support our experimental studies of color centers and superradiance [7]. To this end, we applied the formalism of the quantum theory of open systems, whose central element is the GKLS equation co-authored by A. Kossakowski [8, 9]:

$$\mathcal{L}[\hat{\rho}(t)] = -i[\hat{H}, \hat{\rho}] + \sum_k^{N^2-1} \gamma_k \left(\hat{L}_k \hat{\rho}(t) \hat{L}_k^\dagger - \frac{1}{2} \{ \hat{\rho}(t), \hat{L}_k^\dagger \hat{L}_k \} \right). \quad (1)$$

The model we obtained [6] turned out to be inconsistent with the description proposed by another research group [5], which led to the preparation of a work in which we verify both approaches and indicate significant differences in the predicted physical behavior of the analyzed systems.

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Transient sensitivity of optical atomic clocks and prospects for active-clock–based detection schemes

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Optical atomic clocks provide a powerful platform for probing temporal variations of fundamental constants. Their response to time-dependent perturbations is intrinsically linked to the dynamics of the laser stabilization loop that locks the local oscillator to the atomic transition. In this work, we examine how key servo parameters—such as bandwidth, gain, and operating mode—affect the system’s response to short-lived signals [1].

Motivated by these limitations, we also examine active optical clock architectures, in which the lasing process itself contributes to frequency stabilization and reduces reliance on external feedback. Within our analysis, we compare the response of such systems to transient perturbations with that of conventional passive clocks. While active schemes are still under active development, our results indicate that they may offer distinct sensitivity characteristics, particularly for rapidly varying signals. This suggests that active clocks could provide a complementary perspective in the search for short-timescale variations of fundamental constants.

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Development of cw laser systems in the deep-UV and vacuum-UV ranges

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Reliable and tunable ultraviolet (UV) laser sources are increasingly important for applications in spectroscopy and precision metrology, yet many UV wavelengths remain difficult to access efficiently.

We present a set of UV laser systems that employ cascaded sum-frequency-generation (SFG) stages in nonlinear crystals using different phase matching schemes.

The fundamental light is provided by Diode, VECSEL and Ti:Sa lasers.

The SFG stages are implemented in both single-pass and cavity-enhanced configurations, including one system employing an elliptical cavity mode.

The resulting systems deliver stable, narrowband radiation across multiple regions of the UV spectrum, from 185 nm to 310 nm, demonstrating a versatile and scalable platform for advanced UV laser generation.

High-power optical cavity - towards optical trapping of molecular hydrogen

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The hydrogen molecule (H_2) is a benchmark system for high-precision tests of quantum electrodynamics and searches for physics beyond the Standard Model [1]. Its simple structure enables accurate theoretical predictions; however, the lack of a permanent dipole moment and accessible optical transitions makes it incompatible with standard cooling and trapping techniques for many molecular species, including H_2 [2]. Recent major advances in laser and optical technologies have opened new perspectives for trapping molecules that cannot be cooled using standard techniques. One promising approach is the realization of an optical dipole trap deep enough to directly capture buffer-gas-cooled molecules [3]. This concept relies on the demonstrated feasibility of generating intracavity optical powers on the order of 125 kW [4], which enables trap depths of several kelvin and makes pre-cooling with commercially available cryogenic systems possible. In this work, we present the development and characterization of a high-power optical system designed for dynamic trapping of H_2 molecules in a cryogenic environment. The system is based on a high-finesse optical cavity stabilized using the Pound–Drever–Hall (PDH) technique and driven by a 1064 nm laser source. Efficient coupling to the TEM_{00} mode is achieved using a two-lens mode-matching scheme, while fast modulation of the intracavity field is implemented with an acousto-optic modulator, enabling realization of a time-averaged optical dipole trap. Experimental characterization includes cavity ring-down measurements, providing estimates of mirror reflectivity, round-trip losses, and finesse [5]. These parameters were investigated under both room-temperature and cryogenic conditions. Stable cavity operation and fast switching of the optical field have been demonstrated, confirming the feasibility of generating trapping potentials at the level of a few kelvin.

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Evaluation of wavefront aberrations in cold-atom inertial sensors

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The performance of atomic interferometers has been pushed to the cutting edge in terms of accuracy and sensitivity. Their applications span a wide range of domains, from metrology, tests of fundamental physics to on in the field and in space measurements [1]. One of the limitations of current cold-atom inertial sensors stems from the inhomogeneities, particularly in the wavefront, in the laser light used to manipulate atomic wavepackets [2,3].

Using numerical simulations, we evaluate the impact of retroreflective optics on a standard 3-pulses ($\pi/2$ - π - $\pi/2$) Raman interferometer in a cold-atom gravimeter down to 10^{-8} m.s⁻² [4] and in a gradiometer down to 10^{-9} s⁻² [5]. These results are confirmed by an analytical model based on an atomic source, with normal distributions in position and velocity, interacting with a Gaussian beam, reflected onto optical elements whose defects are characterized by Zernike polynomials. This model can be generalized to other interferometer geometries. It highlights that, in addition to the amplitude of the optical aberrations, the resulting effect will be determined by the ratio between characteristic lengths, associated with the atomic cloud dispersion on the one hand, and to the optical aberrations on the other hand. First, optical aberrations are averaged out when their typical transverse length is smaller than the transverse size of the atomic cloud. Second, since matter-light interactions occur at different locations along the optical axis, the resulting effect will depend on the positional variation between the different pulses relative to the typical propagation length of the aberrations. Finally, when the interrogation time is long enough for the size of the atomic cloud to be comparable to the laser beam radius, the ratio of these lengths determines which atoms form a closed interferometer.

Moreover, these consistent numerical and theoretical approaches enable us to define optical specifications for future cold-atom inertial sensors based on a targeted uncertainty level. Finally, our model will need to be refined to account for the implementation of additional techniques in our gradiometer experiment, such as shaping the laser beam into “top-hat” profiles and using optimal control protocols for tailoring sequences of Bragg pulses [6].

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Development of a pulsed atomic anion source for antiprotonic atom formation

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Antiprotonic atoms are exotic systems in which an antiproton replaces an electron. Due to their unique structure, they provide an interesting platform for studying atomic processes and matter–antimatter interactions. One possible method for producing such systems involves collisions between antiprotons and neutral atoms formed from negative ions. In the AEGIS experiment at CERN, low-energy antiprotons delivered by the ELENA ring can be captured and stored in a Penning trap. To enable the formation of antiprotonic atoms, negatively charged ions may be injected into the same trapping potential. After photodetachment of the excess electron, the resulting neutral atoms can interact with antiprotons and form antiprotonic atoms [1].

This approach requires an efficient, stable, and long-lasting source of atomic anions. For experimental reasons, the anions have to be produced in a separate apparatus, stored in a quadrupole Paul trap, and then delivered on demand as a short ion pulse to the main Penning trap containing antiprotons. We present a negative-ion source based on dissociative electron attachment in electron–molecule collisions. In the source chamber, operated under high-vacuum conditions, iodine molecules are bombarded with monochromatic electrons, producing negative iodine ions. The created anions are accumulated in a multicentre linear Paul trap and can subsequently be extracted in a controlled pulse toward the main experimental chamber.

The device was designed, constructed, and tested at Nicolaus Copernicus University in Toruń as part of the development work for the AEGIS experiment. The presentation will discuss the operating principle of the source, its construction details and preliminary results from laboratory tests [2].

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The $^{13}\text{C}^{18}\text{O}$ $\text{A}^1\Pi(v=2) \sim \text{a}^3\Pi(v=13)$ Indirect Perturbation: Detection, Mechanism, and Surprises

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A direct perturbation between the $\text{a}^3\Pi$ and $\text{A}^1\Pi$ vibrational levels of two electronic states that belong to the same electronic configuration of the carbon monoxide molecule should be unobservably weak because the vibrational overlap integral $\langle \text{a}^3\Pi, v' | \text{A}^1\Pi, v'' \rangle$ for their near degenerate levels is extremely small [1, 2]. Yet level shift and transition intensity signatures of the $\text{a}^3\Pi(v=13) \sim \text{A}^1\Pi(v=2)$ perturbation are unmistakably present in the $^{13}\text{C}^{18}\text{O}$ isotopologue. Detailed study of the $\text{A}^1\Pi - \text{X}^1\Sigma^+(2, 0)$, $\text{B}^1\Sigma^+ - \text{A}^1\Pi(0, 2)$ and $\text{C}^1\Sigma^+ - \text{A}^1\Pi(0, 2)$ spectra, obtained on the VUV- and Vis-FT complementary techniques in the energy regions of the three crossing points (e- and f-symmetry, $|\Omega| = 0, 1, 2$) between the $\text{a}^3\Pi(v=13)$ and $\text{A}^1\Pi(v=2)$ states, reveal that the perturbation pathways are indirect, primarily facilitated by the $\text{e}^3\Sigma^-(v=4)$ state, and that quantum mechanical interferences between the F_{1e} and F_{3e} parts occur (figure 1).

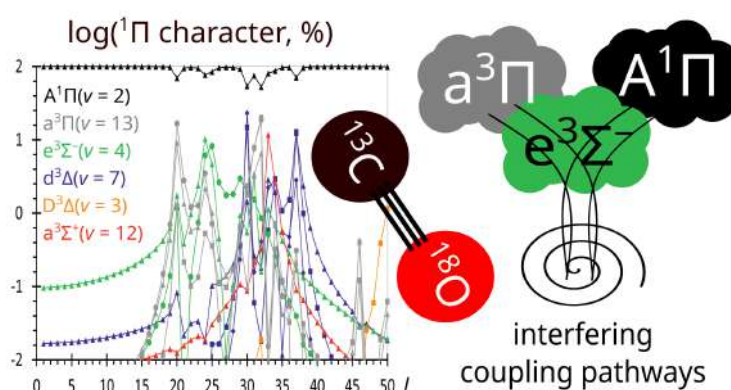


Figure 1: Graphical abstract.

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Dual wavelength high-finesse cavity for neutral mercury clock

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We report on the development and implementation of a high-finesse, dual-wavelength ultra-low expansion (ULE) cavity [1] for laser frequency stabilization in a dual-species neutral mercury optical atomic clock. The system is designed to enable high-resolution interrogation of two sub-hertz clock transitions ($1s_0 - 3p_0$ and $1s_0 - 3p_2$) with improved long-term frequency stability. The reference cavity supports two distinct optical wavelengths (1064 nm and 908 nm) relevant to neutral mercury spectroscopy, with a finesse exceeding 100,000 at both frequencies. This is achieved with engineered dielectric mirror coatings that provide high reflectivity and low optical loss across two spectral regions. Independent Pound–Drever–Hall (PDH) locking schemes [2] are implemented for each wavelength, requiring precise mode matching, polarization control, and suppression of residual amplitude modulation. The cavity is thermally stabilized near its zero-crossing temperature to minimize frequency drift, and active thermal stabilization reduces thermo-optic effects that could otherwise introduce wavelength-dependent shifts in the effective cavity length. By providing a common ultra-stable reference for both lasers, the dual-colour cavity enables narrow-linewidth [3] and low-noise probing of the two clock transitions. This approach significantly enhances spectral resolution, signal-to-noise ratio, and frequency stability, thereby improving the precision and accuracy of clock transition spectroscopy in neutral mercury system [4].

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and deperturbation analysis of the $a^3\Pi$ ($v = 4$) state of $^{12}\text{C}^{16}\text{O}$

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Carbon monoxide (CO) is one of the key molecules in astrophysical spectroscopy, where precise data on its energy level structure are essential for modelling the spectra of planetary and exoplanetary atmospheres. The Cameron system ($a^3\Pi - X^1\Sigma^+$) constitutes an important transition system in the vacuum ultraviolet (VUV) region, widely used, among others, in the analysis of atmospheric emissions of Mars and Venus [1-5].

In this work, a high-resolution absorption spectrum was recorded for the $v' = 4$ vibronic level of the Cameron $^{12}\text{C}^{16}\text{O}$ system using vacuum ultraviolet Fourier transform spectroscopy (VUV-FT) at the DESIRS beamline of the SOLEIL synchrotron [6]. A total of 191 spectral lines, comprising 9 branches, were identified. The wavenumbers of the spectral lines were determined to an accuracy of 0.01 cm^{-1} . The energy terms for the transition under study were also determined.

The rovibronic structure of the $a^3\Pi$ state ($v = 4$) was analysed using an effective Hamiltonian approach implemented in the PGOPHER program [7]. For each vibrational level, a set of 9 molecular constants was determined, describing the level energies, molecular rotation, and intrastate spin-orbit, spin-rotation, spin-spin coupling, as well as Λ -doubling phenomena.

For the $a^3\Pi(v = 4)$ level, deviations from regular behavior were observed and described by determining perturbation parameters. The analysis showed that the observed irregularities arise from interaction with the $a^3\Sigma^+$ state and significantly affect the structure of $a^3\Pi$.

The obtained molecular parameters, together with highly accurate experimental wavenumbers, represent a significant extension of the available spectroscopic data for CO and can be directly implemented in databases (e.g., ExoMol) as well as in VUV spectral modelling.

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New beyond-Voigt line-shape profile recommended for the HITRAN database

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Advances in high-resolution molecular spectroscopy have shown that the conventional Voigt profile is insufficient for state-of-the-art applications, motivating the development of beyond-Voigt models for spectroscopic databases and atmospheric retrievals. By incorporating speed-dependent collisional broadening and shifting together with Dicke narrowing caused by velocity-changing collisions [1], combining them with efficient numerical implementation [2], the Hartmann-Tran (HT) profile [3] became the recommended high-accuracy line-shape model in HITRAN. However, practical applications revealed important limitations, including singular behaviour in the temperature dependence of velocity-changing collision parameters and difficulties in treating gas mixtures. We present a modified Hartmann-Tran (mHT) profile that preserves the physical completeness and computational efficiency of the HT profile while removing its main practical limitations.

The mHT profile [4] is intended as a next-generation beyond-Voigt model for precision spectroscopy and atmospheric applications. It additionally incorporates the β -correction term, derived from the more physically justified billiard-ball model, improving the treatment of velocity-changing collision and the overall physical consistency of the profile. The model retains computational performance comparable to the HT profile, enabling direct use in large-scale radiative-transfer and spectral-fitting calculations, while naturally supporting line mixing and improved temperature parametrization. The mHT profile is proposed as a new standard for advanced spectral line-shape modelling.

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A Three-Colour MOT for Sustained Superradiant Lasing

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Magneto-Optical Traps (MOTs) leverage laser cooling and a spatially varying magnetic field to create a trap for neutral atoms. Atoms trapped in a cavity can synchronously emit light - superradiance. At the Niels Bohr Institute, superradiant lasers have been realised with measured linewidths almost an order of magnitude below the natural linewidth of the lasing transition [1].

To realize steady state superradiance in strontium, the atoms are initially trapped in a blue MOT ($\sim$ mK temp.) followed by a red MOT ($\sim$ μ K temp.) and released within a cavity. Here, the atoms undergo pumping and synchronously emit through the cavity mode. Linewidth measurements are Fourier limited by the atoms leaving the interrogation zone due to heating. As proposed in [2], this can be overcome by employing another stage of cooling during superradiance.

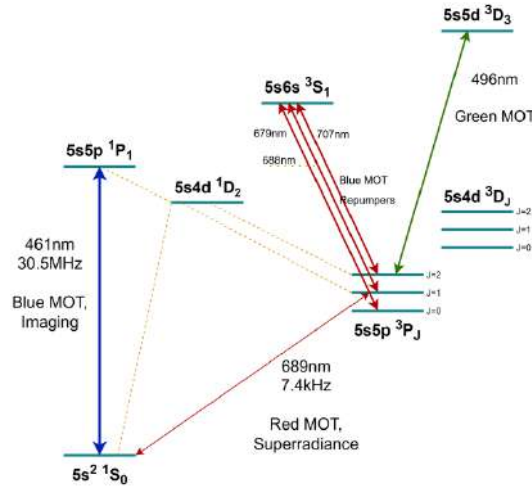


Figure 1: Relevant transitions in Sr - dashed lines indicate decays, $^3P_{0,2}$ have long lifetimes

Most of the atoms are parked in the $^3P_2$ metastable state during lasing, and they then do not participate in the superradiant emission. A cycling transition from $5s5p\ ^3P_2$ to $5s5d\ ^3D_3$ can be used as a MOT to cool down these atoms [3]. Other decay pathways from the $^3D_3$ bring them back down to $^3P_{1,2}$, from where they either re-enter the cooling cycle or the lasing cycle.

Here, we implement a three-colour MOT and perform characterization on the atom number, temperature and its effect on the superradiant emission. By introducing this laser-cycle cooling, we push the strontium platform a step closer to fully continuous collective atomic behaviour.

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Zinc as a platform for precision metrology

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Alkaline-earth-like atoms are central to precision metrology, combining strong cooling transitions with narrow optical lines for clocks and tests of fundamental physics. While strontium and ytterbium are established platforms, group-IIB elements such as zinc, cadmium, and mercury offer a complementary route with deep-ultraviolet transitions, reduced black-body-radiation sensitivity, and short wavelengths advantageous for precision measurements and spatial control. In this work, we explore zinc as a platform for precision spectroscopy and quantum control. We have developed a 214 nm deep-ultraviolet laser system for cooling and trapping, enabling the first realization of a zinc magneto-optical trap [1, 2]. In parallel, we perform high-resolution atomic-beam fluorescence spectroscopy of the narrow $^1S_0 \rightarrow ^3P_1$ intercombination line at 308 nm, which is relevant for second-stage cooling and provides a testbed for isotope-shift measurements and systematic studies. As a next step, we will use magnetic-field-induced quenching to make the ultra-narrow $^1S_0 \rightarrow ^3P_0$ clock transition at 310 nm weakly accessible in the atomic beam. This measurement will narrow the search range and establish the transition frequency before transferring the spectroscopy to ultracold zinc atoms in an optical lattice. In this trapped geometry, zinc combines short wavelengths and narrow transitions, making it a promising candidate for high-precision clock spectroscopy, quantum simulation, and quantum information processing in tightly confined atomic arrays.

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High-resolution spectroscopy of the oxygen B band for atmospheric applications and HITRAN2024

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The oxygen molecule (O_2) plays a fundamental role in atmospheric spectroscopy due to its nearly constant amount fraction throughout the Earth's atmosphere. As a result, oxygen absorption lines are widely used for the retrieval of pressure and temperature profiles, total air column density, and for improving the accuracy of greenhouse gas and air pollutant retrievals. Reliable spectroscopic line-shape parameters of oxygen are therefore essential for atmospheric remote sensing and radiative transfer applications.

The O_2 B band ($b^1\Sigma_g^+(v=1) - X^3\Sigma_g^-(v=0)$), centered near 690 nm, is the second strongest atmospheric absorption band of oxygen. Although it is approximately fifteen times weaker than the strongest A band, this lower intensity reduces saturation effects over long atmospheric paths, making the B band particularly valuable for satellite observations. It is currently used in atmospheric missions such as EPIC/DISCOVER and ESA Sentinel-5 and Sentinel-5P.

Until recently, accurate air-broadened line-shape parameters for the O_2 B band were unavailable due to the relatively weak intensities of its transitions. Recent high-resolution and high signal-to-noise measurements enabled detailed analysis using the speed-dependent Nelkin–Ghatak profile, providing the first consistent set of beyond-Voigt line-shape parameters and their temperature dependences for selected transitions in this band [1].

The resulting dataset was used to model the dependence of line-shape parameters on the lower-state rotational quantum number J'' within the measured range [2]. The analysis reveals that several parameters exhibit distinct trends for the P and R branches and, in some cases, also between individual sub-branches. An example is the dimensionless parameter a_S , which describes the speed dependence of the collisional line shift. The derived parameterization can be extended toward higher rotational quantum numbers using trends established for the O_2 A band. The resulting dataset provides a comprehensive description of air-broadened O_2 B-band spectra and has been incorporated into the HITRAN2024 spectroscopic database [3].

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High-precision gas thermometry based on broadband optical frequency comb spectroscopy

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Accurate gas temperature measurement is critical in metrology, environmental monitoring, and industrial process control. Conventional contact thermometry in gaseous media suffers from self-heating and radiative effects, limiting its accuracy and traceability[1]. To address this, non-contact spectroscopic methods have been developed [2, 3]. Among them, rovibrational line-intensity ratio thermometry (LRT), which retrieves temperature from Boltzmann-distributed molecular populations, is promising due to its wide pressure range and reduced sensitivity to line-shape effects [4, 5, 6, 7]. In particular, the combination with broadband spectroscopy enables multi-line analysis, significantly improving measurement precision and robustness.

In this work, broadband spectroscopic measurements and temperature retrievals are performed for the CO (1–0) and CO₂ (30012) bands using optical frequency comb-based techniques. For the CO (1–0) band, a mid-infrared optical frequency comb combined with a Fourier-transform spectrometer (OFC-FTS) [8, 9] achieves high signal-to-noise spectra with a short 72 cm path length, leveraging the strong mid-infrared absorption to avoid multipass or enhancement cavities. Temperature is retrieved from 78 line-intensity ratios in the R branch. For a gas sample stabilized at 298.15 K (± 21 mK), the retrieved temperature is 298.255 K with a statistical uncertainty of 0.137 K, a 4.5-fold improvement over previous near-infrared comb-based systems. For the CO₂ (30012) band, cavity mode-dispersion spectroscopy (CMDS) using a comb-coupled high-finesse cavity is employed. Applying the same thermometric approach, the measured line intensities deviate from the HITRAN database by approximately 1%, further demonstrating the promise of broadband spectroscopy for temperature retrieval and confirming the method's reliability for high-precision spectroscopy and quantitative analysis.

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Robust population inversion by adiabatic passage in a continuous atomic beam for superradiant lasing

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Superradiant lasers offer promising perspective of overcoming limitations displayed in passive optical clocks due to their sensitivity to vibrations and their typically discrete preparation of gain medium. The challenge lies in achieving a continuous emission regime.

The pathway taken by our group is to prepare a continuous atomic beam, population inverted at the cavity location to sustain superradiance as emitters [1]. For population inversion, instead of optical pumping, we choose a scheme based on adiabatic excitation of the atoms, operating continuously on the atomic beam. The atoms, moving across a strongly diverging optical beam, experience a temporal sweep of perceived laser frequency, and are thus excited following an adiabatic passage. In this talk, we present the design, realization and characteristics of this population inversion scheme, the performances achieved in term of efficiency and robustness, and its further outlook in achieving continuous superradiance.

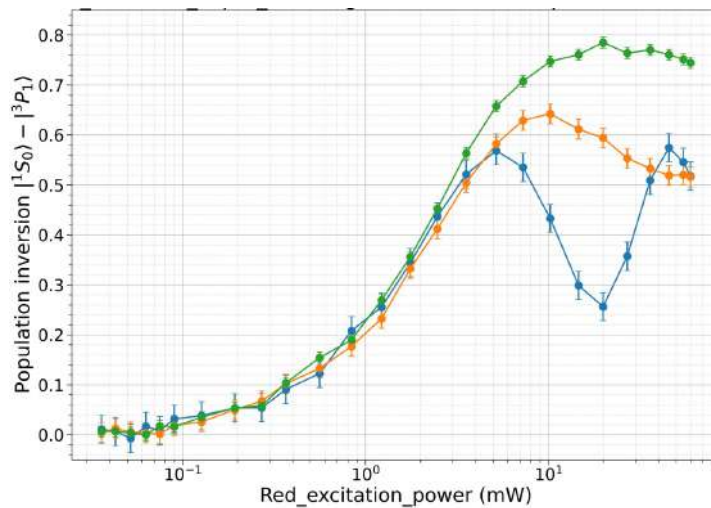


Figure 1: Excitation efficiency as a function of excitation beam power, for atoms crossing the optical excitation beam at different axial positions. The green curve corresponds to an axial position of several Rayleigh ranges from the beam waist (adiabatic regime), the blue curve less than one Rayleigh range (Rabi oscillation dominated regime), and the orange curve in between.

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FT-spectroscopy of the $^{12}\text{C}^{18}\text{O}$ rare isotopologue and deperturbation analysis of the $\text{A}^1\Pi(v = 1 - 3)$ level

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The rotational structure of the $v = 1 - 3$ vibrational levels of the $\text{A}^1\Pi$ electronic state in the rare $^{12}\text{C}^{18}\text{O}$ isotopologue was investigated. The analysis was based on an extensive set of high-accuracy experimental data obtained using two complementary Fourier-transform spectroscopic techniques: (i) *vacuum-ultraviolet absorption spectroscopy* and (ii) *visible emission spectroscopy*.

For each of the $\text{A}^1\Pi(v = 1, 2, 3)$ vibrational levels, a complete deperturbation analysis was performed based on an effective Hamiltonian and the method of simultaneous fitting of term values and molecular constants. The analysis enabled verification of 119 cases of intramolecular interactions potentially occurring in the $\text{A}^1\Pi(v = 1 - 3)$ state. As a result, 29 precise molecular constants and 16 perturbation parameters were determined.

The high-accuracy measurements and verification of all perturbers capable of affecting the $\text{A}^1\Pi(v = 2)$ level within the observed spectral range, as well as the enriched description of the intramolecular interactions through quantifying the fractional $^1\Pi$ character in the investigated rovibronic levels, enabled – for the first time – the identification of indirect interactions between the $\text{a}^3\Pi$ and $\text{A}^1\Pi$ states in the $^{12}\text{C}^{18}\text{O}$ isotopologue. The intermediate perturbers in this case were the $\text{e}^3\Sigma^-(v = 4)$, $\text{d}^3\Delta(v = 7)$, $\text{a}^3\Sigma^+(v = 12)$, $\text{D}^1\Delta(v = 3)$ and $\text{I}^1\Sigma^-(v = 3)$ levels. In turn, the deperturbation analysis of the $\text{A}^1\Pi(v = 3)$ level revealed two additional significant indirect interactions: $\text{a}^3\Pi(v = 14) \sim \text{e}^3\Sigma^-(v = 6) \sim \text{A}^1\Pi(v = 3)$ and $\text{a}^3\Sigma^+(v = 14) \sim \text{A}^1\Pi(v = 3) \sim \text{e}^3\Sigma^-(v = 6)$. In addition, 308 rotational term values of the $\text{A}^1\Pi(v = 1 - 3)$ levels and their perturbers as well as 142 terms of $\text{B}^1\Sigma^+(v = 0, 1)$ and $\text{C}^1\Sigma^+(v = 0)$ levels were determined. Franck-Condon factors, R -centroids for all studied bands, and electronic isotope invariants of the investigated interactions were also calculated.

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Predictive Gaussian Modeling of Spin Squeezing and Inter-Isotope Entanglement in a Dual-Isotope Mercury Comagnetometer

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Thermal mercury (Hg) vapor combines a large atomic number density at moderate temperatures with long-lived ground-state nuclear-spin coherence, making it a promising platform for quantum-enhanced magnetic-field sensing via the realization of measurement-induced macroscopic entanglement [1].

We present a predictive model for a dual-isotope $^{199}\text{Hg}/^{201}\text{Hg}$ comagnetometer, in which a single linearly polarized, off-resonant optical probe near 254 nm, addressing the $6^1S_0 \rightarrow 6^3P_1$ transition, continuously measures the collective spin projection along the probe propagation direction. The measurement is performed through spin-dependent Faraday rotation of the probe polarization, which is detected using balanced optical polarimetry.

Within a linear-Gaussian approximation, we describe the atom–light interaction by tracking the time evolution of the mean values and covariance matrix of the relevant collective atomic spin and photonic Stokes operators [2]. The state space includes the collective spin-1/2 ensemble of ^{199}Hg , a complete $\text{SU}(4)$ multipole basis for the spin-3/2 ensemble of ^{201}Hg that captures tensor alignment dynamics, and the relevant Stokes components of the optical probe. The dynamics are implemented as a discrete-time Gaussian moment update: at each time step, the collective mean vector and covariance matrix are propagated under coherent Zeeman evolution and dispersive atom–light coupling, including both vector and tensor light-shift terms [3]. Effects beyond the ideal weak-QND measurement regime, including probe-induced optical pumping, probe absorption, finite detection efficiency, and hot-vapor relaxation and diffusion, are incorporated through the corresponding drift, diffusion/noise, and readout maps.

This numerical framework enables us to identify operating regimes in which the Faraday rotation measurement generates spin squeezing while tensor light shifts are minimized through suitable choices of probe detuning, polarization, and magnetic-field geometry [4]. It also provides a direct covariance-level route to test inter-isotope entanglement between the collective ^{199}Hg and ^{201}Hg atoms using entanglement witnesses such as Duan–Simon inseparability criterion [5, 6]. Finally, the model predicts the comagnetometric relative precession phase between the ^{199}Hg and ^{201}Hg spin ensembles, allowing us to quantify the expected quantum enhancement, relative to the standard quantum limit, in the sensitivity of the differential phase measurement.

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The FAMU experiment at the RIKEN-RAL muon facility: precision measurement of the ground-state hyperfine splitting in muonic hydrogen

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The FAMU experiment aims at a high-precision determination of the ground-state hyperfine splitting in muonic hydrogen using laser spectroscopy. This quantity is directly related to the proton Zemach radius and, therefore, provides a sensitive probe of the proton magnetic structure. The measurement exploits the high-intensity pulsed muon beam available at the RIKEN-RAL Muon Facility at the ISIS Neutron and Muon Source, STFC Rutherford Appleton Laboratory, UK.

The experimental setup comprises a gaseous target filled with a hydrogen–oxygen mixture, a high-power mid-infrared laser system used to drive the hyperfine transition, and a detection system based on an array of lanthanum bromide detectors together with a high-purity germanium detector for the observation of the characteristic muonic X-ray lines associated with the transition. A beam hodoscope is used to measure the beam profile and intensity.

Data taking was carried out between 2023 and 2025. A summary of the data taking and the progress of the ongoing data analysis will be presented.

The ground state hyperfine splitting in muonic hydrogen experiment (HyperMu) at PSI

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A muonic hydrogen atom is formed when a muon, which is about 207 times heavier than an electron, replaces the electron in a hydrogen atom. The larger mass of the muon greatly increases the overlap between the muon wavefunction and the proton, thereby enhancing sensitivity to the proton structure effects. The HyperMu experiment at PSI aims to perform the first measurement of the ground state hyperfine splitting in muonic hydrogen (μp) with 1 ppm precision using pulsed laser spectroscopy. This accuracy enables a precise determination of the proton structure contributions at the 100 ppm, including the Zemach radius and the proton polarizability.

To measure the ground state hyperfine splitting in μp , we developed a unique pulsed laser system delivering 2.5 mJ pulses of 50 ns length at a wavelength of 6.8 μm , triggered randomly upon muon detection. We report on the latest laser development, the several developments of the detection system, and the optimization of the experimental parameters in preparation for the planned measurement at the end of this year.

Hyperfine Structure Analysis of Neutral Terbium (Tb I) using Fourier Transform Spectroscopy

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Terbium ($Z = 65$) is a rare-earth element and its spectrum is highly dense and complex due to the open $4f$ electron shell. Tb has a single stable isotope, ^{159}Tb ($I = 3/2$), and possesses a magnetic dipole moment of $\mu_I = 2.014(4) \mu_N$ and an electric quadrupole moment of $Q = 1.432(8) \text{ b}$ [1]. These nuclear properties give rise to significant hyperfine interactions, directly influencing the magnetic dipole A and electric quadrupole B hyperfine structure (hfs) constants and leading to complex, multi-component spectral line profiles. Hyperfine structure of Tb have been investigated in the recently and in the past (see [2, 3] and references therein).

The hyperfine structure of neutral terbium (Tb I) is being investigated using high-resolution Fourier transform spectroscopy. The Tb spectra have been recorded from a hollow cathode discharge source using a Bruker IFS 125HR FT spectrometer at the Laser Center of the University of Latvia, enabling the observation of a broad spectral range from UV to NIR (from 12500 cm^{-1} to 34500 cm^{-1} or from 290 nm to 800 nm).

Magnetic dipole and electric quadrupole constants were determined for more than 50 energy levels by hfs analysis, each constrained by at least three observed transitions. The hfs of all these levels are reported here for the first time. The hyperfine structure of spectral lines was analyzed using the FITTER program [4] and the analysis is currently in progress.

Although terbium is observed predominantly in its ionized form in stellar spectra, accurate Tb I data provide constraints on atomic structure and spectroscopic modeling [5]. Hfs significantly influences line profiles, motivating further laboratory studies aimed at the deconvolution of blended spectral lines and enabling improved identification of Tb I and Tb II lines. The dataset presented here contributes to this effort. In this conference, we will present the current status of the investigation.

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Low energy μ^+ microbeams for fundamental physics

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Low-energy beams of positive muons, at tens of keV and below, facilitate experiments in the field of fundamental particle physics, such as muonium spectroscopy and gravitational experiments [1] as well as numerous material science applications using the muon-spin resonance (μ SR) technique [2]. Current sources of muons suffer from large spatial and momentum spread, with transverse sizes on the $\sim$ cm scale, which limits the precision of previously mentioned experiments. The challenge of improving the beam quality stems from the relatively short lifetime of muons ($\sim 2.2 \mu$ s). Formation of microbeams of positive muons would pave a way for novel experiments testing the Standard Model of Particle Physics, for example searches for the muon electric dipole moment (μ EDM) [3].

At the Paul Scherrer Institute (PSI) we are developing a novel concept of phase-space cooling of positive muon beams (μ Cool) [4]. Muons of a few MeV are stopped in a cryogenic helium gas target with a vertical density gradient, placed in a homogenous magnetic field combined with a complex electric field. By spatially tuning a frequency muons' collisions with helium atoms, we engineer muons' drift directions inside the gas target, which leads to transverse and longitudinal compression of the muon beam to the sub-mm size and cooling to a few eV energies [5]. Consequently, muons are extracted from the helium gas target to the vacuum via windowless orifice, demonstrating the feasibility of generating low-energy and high-brightness beams of positive muons. Future steps will involve extraction out of the strong magnetic field and re-acceleration to keV energies to provide novel high quality muon beams to experiments. Tunable energy range at the acceleration stage, together with future High Intensity Muon Beam (HIMB) upgrades of the CHRISP facility at PSI [6], will pave a pathway to new generation precision measurements and development of new imaging technologies.

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Prospects of probing atomic parity violation with structured light

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Atomic parity violation (APV) provides a unique low-energy probe of the electroweak sector of the Standard Model. While high-precision measurements in systems such as cesium and ytterbium have demonstrated the power of this approach, further progress calls for novel experimental strategies. In this contribution, we present a theoretical study of the prospects of structured light fields in APV investigations. As an example, we consider the weak-interaction-induced mixing of the 2s and 2p states in hydrogen-like systems, where the resulting E1-M1 interference gives rise to a parity-violating signal in the photoexcitation rate. In this context, we explore the use of twisted Bessel beams and more advanced vector light fields as tools for gaining additional control over this signal. In particular, we show that a coherent superposition of radially and azimuthally polarized beams enables continuous modulation of the E1–M1 interference term via their relative phase. Furthermore, we argue that a radially polarized beam can be exploited for background suppression within the so-called Stark interference scheme.

Excited electronic states of the helium dimer including relativistic, adiabatic, and QED effects

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The helium dimer constitutes a unique system situated at the boundary between few- and many-body physics. All excited electronic states of He_2 are of Rydberg character, making it a candidate for laser cooling studies. We present highly accurate *ab initio* potential energy curves for the low-lying excited states of the helium dimer utilizing state-of-the-art coupled cluster and full configuration interaction methods. We employ newly developed basis sets reaching up to the cardinal number $X = 10$. To ensure exceptional final accuracy, we incorporate all relevant corrections, including relativistic, QED, adiabatic, and nonadiabatic effects, achieving a theoretical accuracy reaching 1.0 cm^{-1} at the potential energy minima. These results establish a benchmark for calculations in orbital basis sets at the interface of few- and many-body regimes and provide a foundation for guiding spectroscopic experiments and identifying optimal excitation paths.

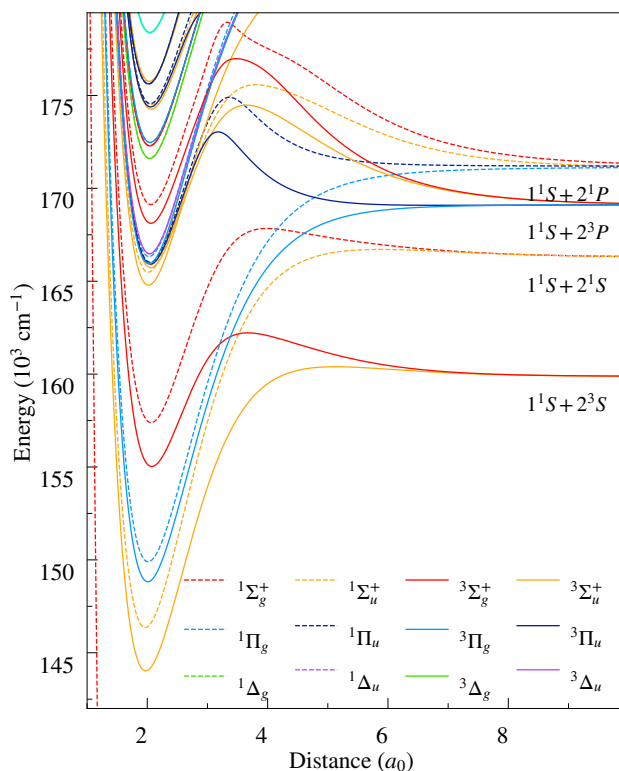


Figure 1: BO PECs calculated for the electronic states corresponding to the first four asymptotes.

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Triatomic YbCaF molecules for measurement of the nuclear magnetic quadrupole moment of Ytterbium 173

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Precision measurements with atoms and molecules provide sensitive probes of physics beyond the Standard Model, often accessing energy scales far beyond those directly accessible with particle accelerators. In particular, polar molecules containing heavy nuclei offer enhanced sensitivity to time-reversal-symmetry-violating nuclear moments through their strongly polarised electronic structure.

Here, we describe a new experiment to assemble YbCaF molecules; Yb-173 atoms will be loaded into optical tweezers alongside CaF molecules, and the two species will be associated via a Feshbach resonance. Triatomic YbCaF is predicted to have strong sensitivity to new physics and, as it is non-linear in its ground electronic and vibrational state, exhibits closely spaced parity doublets which help suppress major sources of systematic errors. We report on current progress toward the association of YbCaF and outline the next steps toward its realisation for precision measurement.

Joint Optimization of Source and Detection System in Entanglement Based BB84 Protocol

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Various imperfections in realistic setup components limit the performance of quantum key distribution (QKD) protocols in terms of both the maximum secure transmission distance and the achievable key generation rate. One of the most effective ways to maximize the performance of a QKD protocol is to use temporal filtering [1] [2]. In this method, the receiver optimizes the detection windows based on the signal parameters in order to minimize the effect of dark count rate and the noise introduced in the quantum channel. However, the detection windows cannot be made infinitely short, because on the one hand the detectors cannot measure the detection times with infinite precision and on the second hand, the signal always has some finite temporal bandwidth. This may be an issue, especially if the dispersion is present in the fibers. Therefore, to maximize the secure key rate, the detection windows and the source parameters should be jointly optimized.

In this work, we study the entanglement-based BB84 protocol, where information is encoded in the polarization of photon pairs generated via spontaneous parametric down-conversion (SPDC) with a pulsed pumping laser. We perform the joint optimization of source parameters and detection system used by Alice and Bob in order to improve the performance of the protocol in a realistic set-up. We take into account several key parameters of the source, including the crystal's phase-matching function width, pump pulse duration, and number of the photon pairs emitted per one use of the source. For the detection system, we optimize the detection windows taking into account several characteristics of the setup, such as, timing jitter, dead time and dark count rate. Finally, we include transmission losses in the quantum channel. In our work, we first optimize the detection windows for a fixed set of source parameters. This is done by considering both an ideal scenario, with no dark counts or timing jitter, and a realistic scenario where non-zero dark counts and timing jitter are included. We demonstrate that, under realistic conditions, it is possible to define optimized detection windows for both Alice and Bob that maximize the key generation rate. In the next step, we illustrate how changes in the source parameters influence the key generation rate. In our analysis, we examine two cases: strongly correlated photon pairs and photon pairs with no correlation generated from the SPDC source. Our results show that, depending on the level of correlation, the optimized values of various realistic parameters can differ significantly. Finally, we conclude our study by performing a joint, simultaneous optimization of both the source and the detection system as a function of transmission loss. Our work is an important step towards refining practical parameter values for realistic QKD systems across wide range of experimental conditions.

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Optical Skyrmions irradiating an atomic medium

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Structured light-matter coupling enables the control, manipulation, and information encoding in quantum materials via fine-tuning of light degrees of freedom. Among those, orbital angular momentum (OAM) has recently gained traction both in the theory of OAM transfer processes and in advanced optical applications [1].

Motivated by optical vortex beams interacting with media [2], here we consider an optical skyrmion beam, a superposition of oppositely oriented circularly polarized components, irradiating an atomic medium showing a Lambda-transition model.

We investigate the possibility of transferring OAM from the incoming skyrmion beam to both the medium and the emitted beam. First, we consider the optical beam coupled to atoms using numerical simulations with GRANAD [3]. Then, we study the time evolution of the intensity profile and the spatially dependent polarization states of the optical skyrmion beam due to propagation by analytically solving the Maxwell–Bloch equations. Finally, we consider further implications of the topological light-matter paradigm for information storage.

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Discrete time quantum walk of locally interacting walkers

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In this work, we introduce a general model for local interactions between quantum walkers conditioned on the internal state of their coins. By choosing their particular case, we systematically study the impact of these interactions on the dynamics of two initially localized and noncorrelated walkers. Our general interaction framework, which reduces to several previously studied models as special cases, provides a versatile platform for engineering quantum correlations with applications in quantum simulation, state preparation, and sensing protocols. It also opens up the possibility of analyzing many-body interactions for larger numbers of walkers.

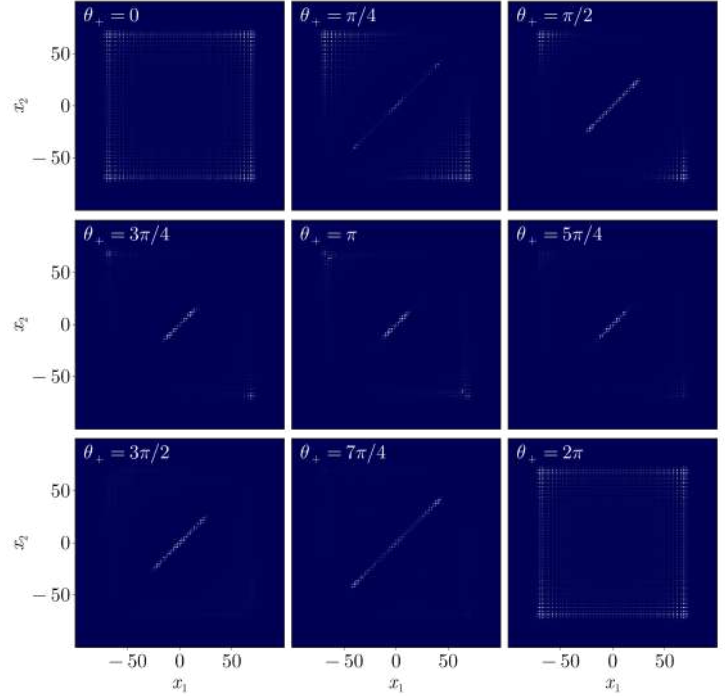


Figure 1: The two-particle density distribution $P(x_1, x_2; t)$ after $t = 100$ time steps for different interaction parameters.

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Floquet treatment of polar quantum system ultrastrongly coupled with light

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We consider a two-level polar quantum system subjected to a classical plane-wave laser drive $\mathbf{E}(t) = \mathbf{E}_0 \cos(\omega t)$ with the frequency $\omega \approx \omega_{eg}$ near-resonant with the system transition [1]. The system is described by the Hamiltonian $H(\omega t) = \frac{1}{2}(\omega_{eg} + g_z \cos(\omega t))\sigma_z + g_x \sigma_x$, where the driving frequency ω is assumed to be high in comparison with the detuning $\omega_{eg} - \omega$, and the transverse coupling strength g_x , while the longitudinal coupling strength g_z is assumed to be of the order of ω . Such an arrangement corresponds to the longitudinal ultrastrong coupling regime which can be implemented, e.g., in atomic lattices [2]. To treat this problem analytically, we first get rid of diverging terms (ω_{eg} and g_z diverge when $\omega \rightarrow \infty$) by using prescribed unitary transformations, and then we obtain a Floquet effective Hamiltonian and a micromotion operator up to first order in the presence of inverse frequency expansion [3]. Additionally, we obtain an exact effective Hamiltonian by using numerical integration of flow equations with the Toda generator [4]. Figure 1 represents the dynamics calculated by numerical integration of the Schrodinger equation in comparison with the analytically obtained effective Hamiltonian and micromotion operators. The resulting analytical approach based on both the effective Hamiltonian and the micromotion can accurately describe small deviations that appear on top of the main Rabi oscillations (Fig.1).

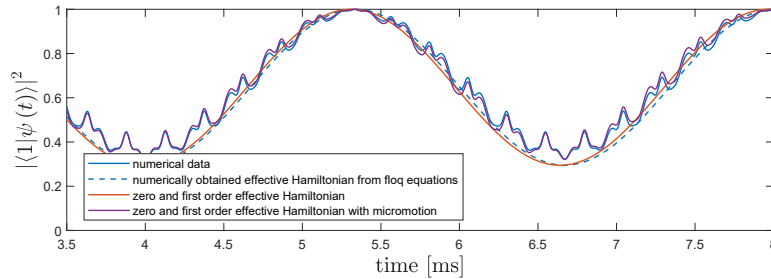


Figure 1: Comparison of the dynamics obtained in four different ways: direct integration of the Schrodinger equation (blue solid line), the exact Floquet effective Hamiltonian obtained from the integration of the flow equations (blue dashed line), analytically obtained Floquet effective Hamiltonian up to the first order (red solid line), and the same as previous but additionally with the analytically obtained micromotion operator up to the first order (purple solid line). The parameter values $\omega = 4.122 \times 2\pi$ kHz; $\omega_{eg} - \omega = -0.2 \times 2\pi$ kHz; $g_z = 0.8\omega$; $g_x = 0.5 \times 2\pi$ kHz have been selected in accordance with atomic lattice parameters in [2].

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A Zeeman Slower of AIF molecules

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AIF is an attractive candidate for laser cooling: it can be produced in large quantities, is deeply bound, and provides a strong cooling transition in the deep ultraviolet. Like alkaline-earth atoms, it also possesses a spin-forbidden transition that can be used for narrow-line cooling. Increasing the density of a magneto-optical trap (MOT) of AIF is an important first step toward transferring laser-cooled molecules into an optical dipole trap, where collisions and evaporative cooling can be studied on the route to quantum degeneracy.

I will present the design and construction of a Zeeman slower (Fig 1.c) aimed at increasing the slowing efficiency and MOT density of AIF molecules. To guide the design, we first calculate the scattering rate of AIF in the Zeeman slower and compare with experiments. We then perform Monte Carlo trajectory simulations (Fig 1.a) to predict the slowing efficiency and determine the relevant engineering constraints, and we model the magnetic-field profile of the slower in COMSOL (Fig 1.b). The immediate next steps will involve experimentally slowing AIF molecules and comparing time-of-flight measurements with both numerical simulations and frequency-chirping methods.

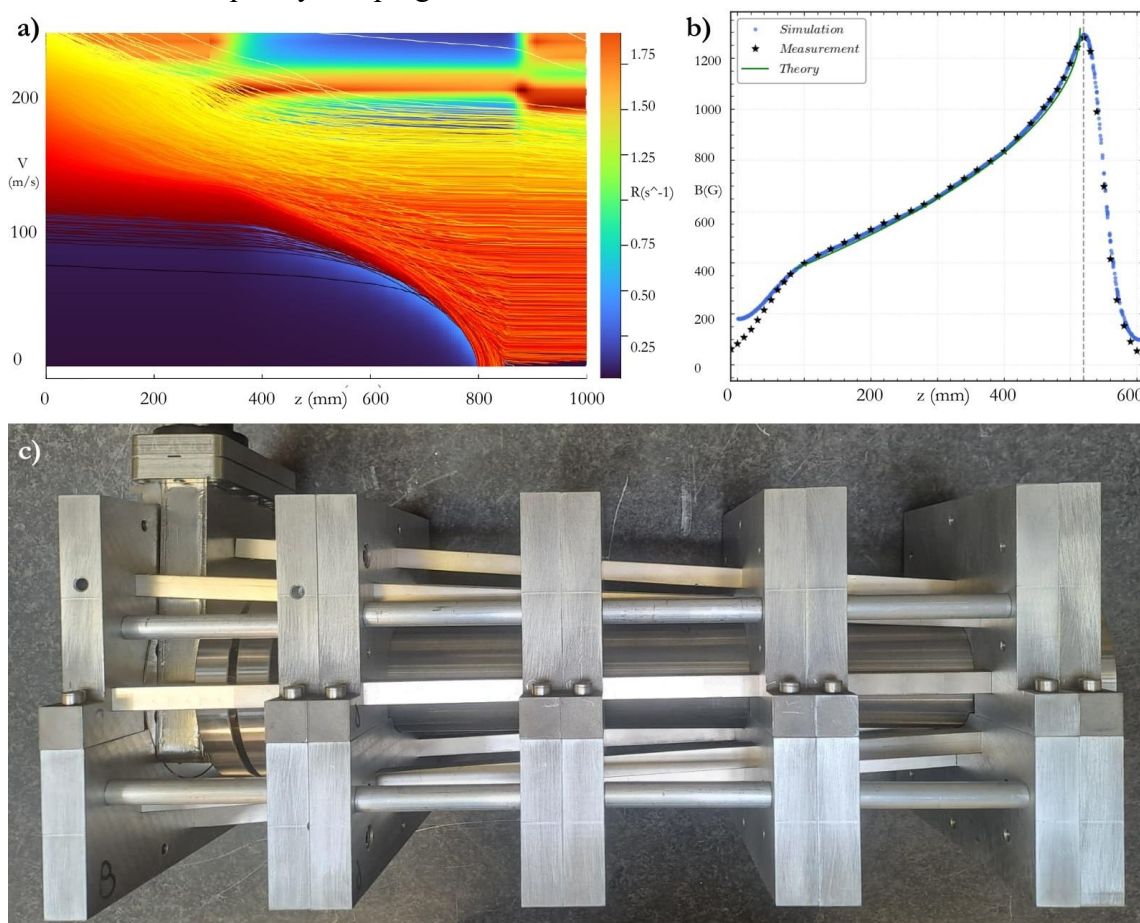


Figure 1: **(a)** Phase-space distribution obtained from Monte Carlo trajectory simulations. **(b)** Magnetic field profile of the molecular Zeeman slower. **(c)** NdFeB magnets arranged in a Halbach configuration.

Selective Preparation of Collective States via SUPER Excitation: Toward Bio-inspired Energy Efficient Configuration

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Here, we theoretically show that the selective and efficient preparation of collective states (super- and sub-radiant states) for two dipole-coupled quantum emitters at deep-subwavelength separation is possible via the Swing-UP of quantum Emitter population (SUPER) excitation scheme [1]. Relying on two off-resonant time-overlapped picosecond Gaussian pulses, the core essence of the SUPER scheme [2] enables near-unity population inversion into collective states by reasonably accessing the ‘pure layer of electromagnetic interaction’ amid a certain amount of environmental decoherence (Figure 1). This eventually offers opportunities to directly witness the signature radiative features of the super- and sub-radiant states. Our scheme enables single-photon generation [1], which, in principle, could operate at elevated temperatures [3]. Furthermore, our study importantly attempts to justify the use of the Markovian master equation approach in the evolving landscape of bio-inspired energy-efficient configurations [4], which is, of course, a much simpler model than reality.

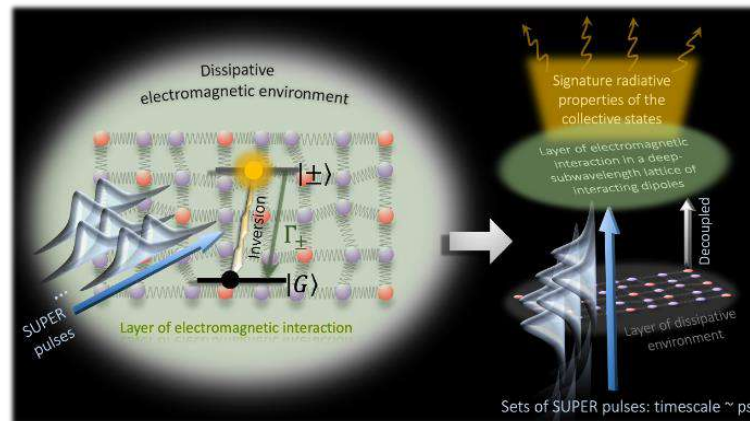


Figure 1: Schematic representation [1]: the sets of SUPER pulses reasonably access the ‘pure layer of electromagnetic interaction’ between coupled quantum emitters at deep-subwavelength separation, even in the presence of environmental decoherence. This decoherence is accounted for by factors such as phonons (shown as lattice vibrations) and on-site energy imperfections (represented by the colors in the background lattice). This process leads to highly efficient inversion from the ground state $|G\rangle$ into collective states $|\pm\rangle$, thereby facilitating direct observation of their signature radiative features.

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Purcell enhancement by the edge states of zig-zag graphene nanoflakes

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Graphene nanoflakes with zig-zag edges exhibit distinct and highly localized edge states [1,2] that impart metallic character to the edges, while the interior remains insulating. This pronounced spatial variation in electronic behaviour makes such systems particularly attractive for nanophotonic applications. When a quantum emitter is placed near the flake[3], coupling to these edge states can significantly enhance its spontaneous emission rate, whereas the insulating bulk contributes minimally. These edge states are geometric rather than topological in origin, rendering them sensitive to external perturbations. In this work, we analyse the behaviour of these states across various nanoflake geometries like triangular, hexagonal, and rhombic, focusing on their stability under electron-electron interactions and doping. We find that in the absence of interactions, coupling to edge states consistently enhances the emitter's decay rate. However, the persistence of these edge-induced transitions depends strongly on sublattice symmetry [4]: sublattice-balanced geometries support edge states even under weak interactions, while sublattice-imbalanced structures lose them rapidly. Interestingly, we demonstrate that careful doping can partially restore edge-state transitions in sublattice-imbalanced flakes, offering a pathway to engineer and control light-matter interactions in graphene nanostructures through both geometry and electronic tuning.

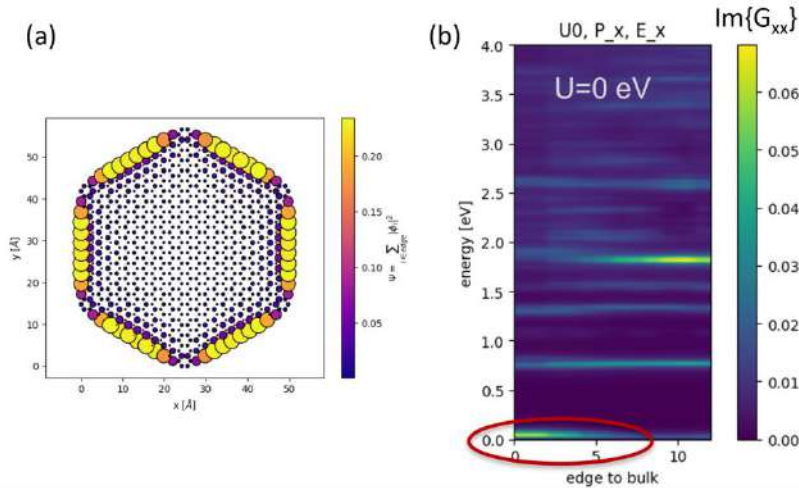


Figure 1: (a) Geometric edge states of a hexagonal zigzag graphene flake. (b) Imaginary part of scattered Green's function as a function of the position of the quantum emitter from edge to bulk. Edge-enhancement is marked.

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On the impact of plasmonic character of optical resonances on Purcell enhancement at the atomic scale

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Controlling quantum emission in nanophotonic systems relies on the nature of optical resonances in the surrounding material. In classical nanophotonics, metal nanostructures enhance the local density of states through plasmonic resonances, yet with absorption losses, whereas semiconductor-based cavities provide field enhancement with reduced dissipation. At the nanometer scale, an additional mechanism arises due to the quantum-mechanical nature of scatterers, where resonances occur at intrinsic electronic transition frequencies. While the distinction between collective (plasmonic) and single-particle (quantum) resonances has been explored [1], their impact on spontaneous emission remains an open question. Here, we investigate whether these resonance mechanisms lead to qualitatively distinct modifications in the emission properties of quantum emitters.

To address this, we study the spontaneous emission of two-level quantum emitters near Su-Schrieffer-Heeger (SSH) chains, modeled within a tight-binding framework [2]. The emitter, treated as a dipole source optically and electronically coupled to the chain, experiences a modified spontaneous emission rate depending on its distance from the structure. Our analysis identifies two distinct interaction regimes governed by the emitter-chain coupling strength and symmetry-breaking effects. By bridging quantum optics and condensed matter physics, this work provides new insights into the fundamental role of resonance character in light-matter interactions at the atomic scale.

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Absorption Spectrum of Bilayer Triangular Graphene Flakes

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The electronic and optical properties of graphene nanostructures are highly sensitive to their geometry, edge topology, stacking configuration, and interlayer interactions. We study small bilayer triangular graphene flakes with armchair and zigzag edges, considering both AA and AB stacking configurations. The electronic structure is modeled using the tight-binding method within the nearest-neighbor approximation, implemented within the GRANAD [1] simulation framework.

We investigate the dependence of the optical absorption spectra on the interlayer hopping strength and the applied gate voltage. Our results demonstrate that both parameters significantly shift the absorption peaks. Differences in absorption spectrum are observed when comparing armchair and zigzag edges, as well as AA and AB stacking configurations. In particular, AA-stacked zigzag flakes exhibit a characteristic single absorption peak, the position of which is highly sensitive to the investigated system parameters.

These findings contribute to the understanding of structure-dependent optical properties in finite bilayer graphene nanostructures and demonstrate the possibility of tailoring their optical response through external fields and interlayer coupling.

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GRANAD: A software package for simulating 2D materials with adatoms under external illumination

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In this contribution, we present GRANAD (GRaPhene NANoflakes with ADatoms), an open-source Python package for simulating the optical and electronic properties of two-dimensional nanoflakes coupled to adatoms under external illumination [1]. The framework combines the tight-binding model to characterize eigenstates and eigenenergies of the hybrid flake-adatom system with the master equation approach to trace the time evolution of charge density under external illumination [2].

GRANAD supports a variety of 2D materials, including graphene, hBN, MoS₂, and SSH chains. In the simulated nanostructure, one can choose different flake geometries, edge terminations, and external field types. Computable quantities include eigenenergies and real-space eigenstate distributions, charge density dynamics, absorption spectra, induced near-fields, and the Energy-based Plasmonicity Index (EPI) [3]. External fields enter the Hamiltonian through external and induced scalar potentials, enabling both linear-response and nonlinear dynamical calculations.

The package is implemented in Python with JAX, which offers just-in-time compilation and GPU acceleration for high computational performance. GRANAD is freely available with full documentation online [4].

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Towards a measurement of the electron's electric dipole moment with trapped YbF molecules

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Ultracold molecules provide a versatile platform for tabletop experiments probing fundamental physics such as measuring the electron's electric dipole moment (eEDM). A promising avenue is to slow eEDM sensitive neutral molecules for trapping, thus extending measurement time. Our recent progress using radiation pressure to slow YbF molecules indicates beam velocities suitable for capture in a magneto-optical trap [1]. This work has improved the closure of leaks out of the cooling cycle as well as incorporated polarization modulation for dark state destabilization. These results pave the way for long-lived trapping of YbF, enabling future eEDM measurements in an optical lattice.

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Beyond Single-Atom Coupling: Self-Organization through Cavity-Induced Atom-Pair Interactions in a Fermi Gas

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Engineering strong interactions in fermionic quantum systems through light-matter coupling enables the exploration of novel phases of matter and the creation of highly correlated states with applications in quantum communication, computation, and metrology. While single-atom-photon coupling has received considerable attention, the collective excitation of atom pairs by single photons can unlock fundamentally new regimes of correlated many-body dynamics [1, 2]. Here, we develop a theoretical framework to describe fermionic atoms in an optical cavity, where each photon interacts simultaneously with a pair of atoms. This pairwise coupling induces an effective atom-atom interaction mediated by the photon field, which we show can lead to spontaneous breaking of translational invariance and self-ordering of the atomic ensemble. By analyzing the structure of the ordered state as a function of pump and atom-atom interaction strength, we map out a phase diagram, unveiling nontrivial solutions that signal transitions between distinct quantum phases, complementing recent studies of cavity-mediated charge and pair-density-wave ordering in strongly interacting Fermi gases [3]. Our results demonstrate how cavity-mediated pair interactions in fermionic ensembles can be harnessed to realize and control emergent ordered phases, paving the way for further studies of exotic light-induced phenomena and the development of novel quantum technologies.

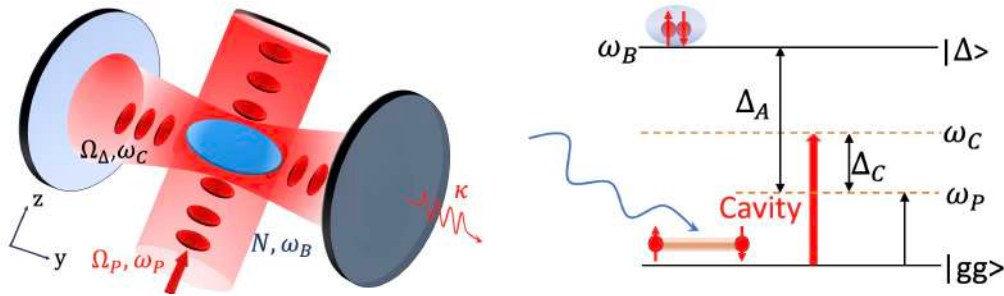


Figure 1: Left: Schematic diagram for the transversal pumping in the cavity. A fermionic cloud inside an optical cavity is pumped by a laser with frequency ω_P transversely. The coupling between the atomic cloud and the cavity field is captured by the single-mode coupling strength Ω_Δ . Right: The diagram of the energy levels relevant of pairs of atoms $|gg\rangle$ and a molecule $|\Delta\rangle$. By Δ_A and Δ_C we denote detunings from the molecular state with energy ω_B and cavity photon energy ω_C , respectively.

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Thermal effects versus magnetic field effects in the study of nitrogen colour centres in diamond

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Diamonds with negatively charged nitrogen-vacancy (NV⁻) colour centres have emerged as a prominent material for quantum metrology due to their unique spin and optical properties [1]. Their high photostability, long coherence times, and biocompatibility further extend their applicability to a wide range of environments, including biological systems [2]. The key feature of diamond vacancies, in the context of the issues discussed here, is the pronounced sensitivity of their optically detected magnetic resonance (ODMR) spectra to variations in both temperature and magnetic field strength [3,4,5].

In this contribution, we present the preliminary results of comprehensive multiparameter investigations of NV⁻ centres in diamond, carried out under simultaneous variation of temperature and magnetic field intensity. The experiments are performed using a customized, home-built experimental setup including a confocal microscope with a 520 nm diode laser and a microwave synthesizer with an optimized planar antenna. The setup is integrated with temperature and magnetic field control systems, enabling systematic ODMR signal measurements. The aim of these studies is to support the calibration of a bimodal sensor capable of measuring both temperature and magnetic field, based on the unique properties of NV⁻ centres in diamond.

This work was supported by PhD Boost Program No 0511/SPHD/0004 for doctoral students of the Doctoral School of Poznan University of Technology (in 2026) from University's subsidy (from the Ministry of Science and Higher Education funds), as well as by Ministry of Science and Higher Education within the project No 0511/SBAD/2651 and 0511/SBAD/0026 at Faculty of Materials Engineering and Technical Physics, Poznan University of Technology.

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Davies-Morris-Shore Framework for Multilevel Quantum Batteries: Dark and Funnel States in Interacting Qutrit Systems

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Dark and subradiant states have emerged as a promising resource for stabilizing open quantum batteries against dissipation, yet existing studies are largely limited to qubit ensembles [1]. In this work, we introduce a systematic, thermodynamically consistent framework for identifying long-lived energy storage states in interacting multilevel quantum platforms. By combining the Davies master equation with a Morris-Shore (MS)-type decomposition of dissipative coupling blocks, we analyze a minimal model consisting of two interacting qutrits coupled to a common bath.

We analytically construct three distinct classes of states: dark, bright, and funnel states—the latter being excited states that decay exclusively into protected manifolds. Our derivation of robustness conditions, governed by the ratio of interaction strength to anharmonicity, demonstrates that multilevel ladder structures and exchange interactions enable energetic storage beyond the qubit limit. Numerical simulations confirm that these states exhibit prolonged energy storage under realistic dissipation. Finally, we highlight that high-energy funnel states provide a natural design target for future multilevel quantum batteries, offering a principled basis for protection strategies in superconducting platforms (figure 1).

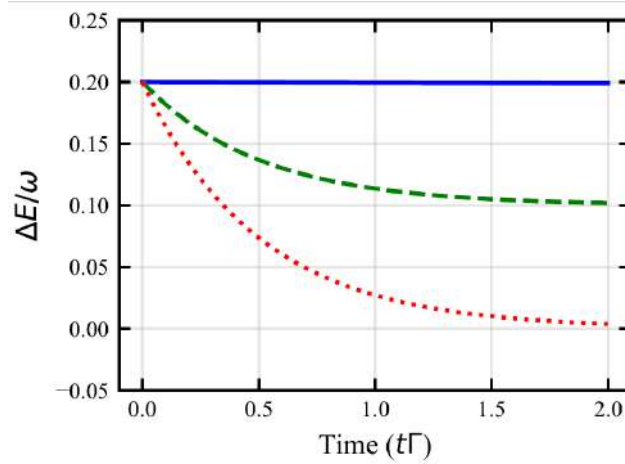


Figure 1: Collective decay dynamics from the source manifold to the protected target manifold via funnel and dark states.

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Atom Transport Benchmark and Parallelization for Scalable Neutral-Atom Quantum Processing

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A central challenge for scalable neutral-atom platforms is moving atoms quickly while preserving trapping, internal-state coherence, and final register quality. To quantify and optimize this “atom move” capability, we introduce a set of practical move-performance metrics, including Transfer Move Efficiency (TME), the probability that an atom remains successfully trapped and usable after a prescribed unitary move, as well as complementary figures of merit such as move time, defect free generation probability, and end-to-end register survival through multi-step rearrangement pipelines.

Using these metrics as a guide, we have demonstrated large-scale performance in the Cryo-Qubit project, achieving defect-free rearrangement of 1024 atoms from an initial ~2070-trap layout via a two-cycle protocol, with defect statistics reduced to the sub-percent level on the final cycle [1]. In parallel, within QuantA, we leverage these capabilities to enable quantum simulation at the few-hundred-atom scale (~300 atoms), where reliable preparation of large, well-ordered registers is a prerequisite for exploring many-body dynamics beyond straightforward classical reach [2].

Looking forward, Multi-Moving Tweezers (MMT) extend atom transport from essentially sequential moves to parallel, waveform-engineered motion of many atoms at once, offering a direct route to faster rearrangement and to more coherent, programmable transport for advanced protocols that combine register assembly with dynamical operations. By increasing parallelism while keeping TME and defect growth under tight control, MMT is poised to substantially accelerate large-register preparation and unlock higher-throughput, higher-fidelity experiments for both digital and analog neutral-atom quantum processing.

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Cavity-QED tools for MBQC with optical binomial-codes

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Measurement-based quantum computation (MBQC) provides a compelling route toward scalable photonic quantum computing. However, its practical realization hinges on the deterministic generation of specific non-Gaussian resource states. While CV-encodings, such as GKP states, have been the subject of extensive theoretical study, their experimental preparation remains challenging. Binomial codes present a simpler and more accessible alternative, but they necessitate a distinct set of operational tools for state generation and manipulation within an MBQC framework.

Here, we introduce a comprehensive toolkit for implementing MBQC using optical binomial codes. We detail a cavity-QED protocol for the deterministic generation of arbitrary superposition states, followed by their controlled emission into a single temporal mode. Furthermore, we provide a protocol for the XY-Pauli measurements, which are essential for MBQC. Our work outlines concrete steps toward integrating these protocols into existing optical atom-cavity architectures, thereby laying out the essential groundwork for their practical application in photonic quantum computing.

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Molecular-state readout via resonant blockade between individual polar molecules and Rydberg atoms

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The integration of Rydberg atoms into arrays of polar molecules offers powerful new tools for controlling and interrogating these systems. Proposals from the last few years [1, 2] highlight how the strong, tunable interactions of Rydberg atoms can enable non-destructive molecular state readout and facilitate atom-mediated quantum gates between molecules. Here we engineer resonant dipole–dipole interactions between individual Rb atoms and RbCs molecules trapped in optical tweezers, which are shown to blockade Rydberg excitation at separations greater than 1 μm . These interaction enable state-sensitive and non-destructive molecular detection and pave the way toward demonstrating atom–molecule entanglement – an essential milestone on the path to implementing Rydberg-mediated quantum gates.

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Switching Rydberg interactions by three orders of magnitude using a terahertz field

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Atom-based quantum computing and simulations rely on the manipulation of interactions between atoms promoted to highly-excited electronic states, so-called Rydberg atoms. The properties of these interactions can be chosen by selection of suitable Rydberg states. An alternative approach to alter the interaction properties during an experimental sequence is to use additional fields driving transitions between Rydberg states with different interaction potentials. This approach allows to decouple the Rydberg excitation process from the interactions and therefore gives access to a finer control of the interaction properties. Microwave fields are commonly used to drive transitions in the Rydberg manifold - however, these only provide access to relatively small changes in principal quantum number n and therefore comparably small changes in interaction strength. In this work, we use terahertz (THz) fields to switch the interaction strength between Rydberg atoms by three orders of magnitude. Interaction switching is demonstrated by detecting the signature of interaction-induced dephasing in a photon storage protocol, as shown in Figure 1 **b**. Level scheme and pulse sequence are shown in **a** and **b**, respectively. We demonstrate coherent driving of a transition on a THz transition and nanosecond timescales using a photon storage-and-retrieval sequence. This reveals Rabi oscillations on the THz transition, as shown in Figure 1 **c**. The work presented on this poster can also be found in [1].

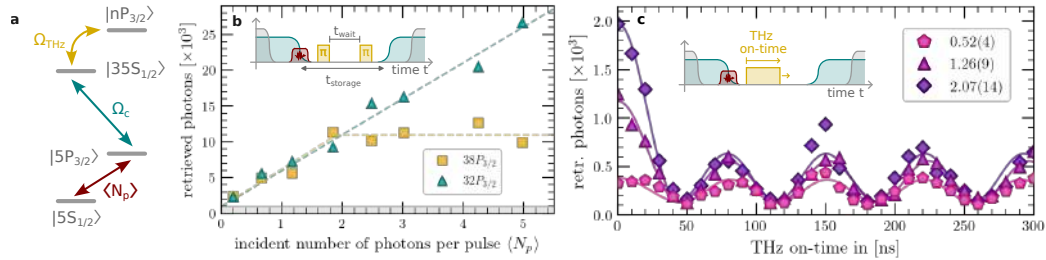


Figure 1: **a** Level scheme for 2-photon excitation of Rubidium to the $|35S_{1/2}\rangle$ state and a THz transition within the Rydberg manifold to a $|nP_{3/2}\rangle$ state. **b** shows the number of retrieved photons as a function of incident probe photon number per pulse, $\langle N_p \rangle$. A linear linear trend is found for THz driving to the $|32P_{3/2}\rangle$ state (blue triangles) with $C_6(32P_{3/2}) = -0.29 \text{ GHz } \mu\text{m}^6$. For the strongly interacting $|38P_{3/2}\rangle$ state (yellow squares) with $C_6(32P_{3/2}) = -0.29 \text{ GHz } \mu\text{m}^6$, the initial increase saturates at $\langle N_p \rangle \approx 2$ incident photons per pulse. Dashed lines are guides to the eye to highlight the different trends. The inset schematically shows the pulse sequence with the colours matching that of **a** and gray representing the dipole trap. **c** shows Rabi oscillations on the $|35S_{1/2}\rangle \leftrightarrow |38P_{3/2}\rangle$ transition at $f_{38} = 607.8 \text{ GHz}$ and the inset shows the pulse sequence. The Rabi oscillations show a suppression in amplitude after an initial cycle through the $|38P_{3/2}\rangle$ state for incident photon numbers $\langle N_p \rangle = 1.26(9)$, $2.07(14)$, denoted as squares and triangles, respectively, but not for $\langle N_p \rangle = 0.52(4)$ (pentagons).

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Relativistic Fock-space coupled cluster calculations of highly charged ions for probing atomic clocks and fundamental symmetries of nature

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Atomic systems offer a plethora of fundamental and functional properties and therefore are of importance to several key implications. Some examples where atoms and ions can serve as important probes include, atomic clocks [1], parity and time-reversal violations [2], and the search for the variations in the fundamental constants. Atomic systems, however, form a many-body complex system for which the exact solution is nontrivial. This poses a serious challenge in the theoretical investigations of the properties of these systems. In this context, relativistic coupled-cluster (RCC) theory is one of the most reliable many-body theories for structure and properties calculations for atoms and ions. In our group at IIT Delhi, we have developed RCC based theories for the properties calculations of closed-shell [3], one-valence [4] and two-valence [5] atomic systems. These theories are implemented as sophisticated parallel FORTRAN programs [6]. The methods and codes we have developed are robust and can compute a plethora of properties, such as excitation energies, transition amplitudes and oscillator strengths, hyperfine splitting constants and energies, dipole polarizabilities, parity and time-reversal violating amplitudes, etc., in different types of atoms and ions. Our calculations also incorporate the corrections from relativistic and QED effects to improve the accuracies of results.

In this talk, I will present our recent studies on highly charged ions (HCIs). We investigate clock-transition properties of HCIs as optical clock candidates and assess their sensitivity to variation of the fine-structure constant. We have studied Cf^{17+} , Cm^{15+} , and Bk^{16+} , which exhibit exceptionally large sensitivity coefficients compared to existing clock candidates. We also explore parity non-conservation (PNC) effects in Li-like HCIs and observe significant enhancement due to strong electron density near the nucleus. These results highlight HCIs as promising systems for precision metrology and tests of fundamental symmetries.

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Heterodyne Atom Interferometry for Ultralight Axion Dark Matter Detection

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The detection of ultralight *axion-like particles* (ALPs) as dark matter candidates represents one of the most important challenges in modern precision atomic physics. Atom interferometry offers a powerful platform for probing such fields through their coupling to atomic spins. However, conventional configurations are fundamentally limited by low-frequency environmental noise and narrow detection bandwidths.

We propose a heterodyne detection scheme that overcomes these limitations by coherently modulating the atomic spin-axion interaction in the laboratory frame. A rotating magnetic field $\mathbf{B}(t) = B_0[\cos(\Omega t)\hat{x} + \sin(\Omega t)\hat{y}]$ induces a controlled spin precession, upconverting the axion-induced energy shift $\Delta E \propto g_{aNN} \nabla a \cdot \mathbf{s}$ from near-DC to a tunable carrier frequency Ω . Synchronous detection at this frequency effectively suppresses $1/f$ noise from seismic and gravity-gradient fluctuations, as well as extend the accessible axion mass range by up to *six orders of magnitude* compared to conventional schemes.

We focus on fermionic ^{87}Sr in the metastable $^3P_2$ state, whose long-lived clock transitions and well-resolved hyperfine structure make it an ideal sensor. Two operating conditions are identified: an adiabatic regime ($\Omega \ll \gamma_F B_0$) to prevent Zeeman transitions, and a weak-field regime ($\mu_B B \ll |A|$) to maintain hyperfine spin locking below the Paschen-Back threshold. For ^{87}Sr ($g_F \approx -0.049$), a 1 mT field allows modulation frequencies up to ~ 100 kHz.

A Ramsey interferometer is shown to be particularly well-suited, acting as a low-pass filter with transfer function $|H(\omega)|^2 = T^2 \text{sinc}^2(\omega T/2)$, offering superior broadband sensitivity over Mach–Zehnder geometries. We further discuss a differential double-interferometer layout exploiting sidereal modulation as a robust discriminator between genuine axion signals and spurious local magnetic perturbations. This scheme provides a new route toward ALP dark matter searches with quantum-enhanced atomic sensors.

Keywords: Atom interferometry · Axion dark matter · Heterodyne detection · neutral Sr · Precision metrology

Laser Spectroscopy measurements of ^{169}Tm in the atomic beam unit

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High-resolution laser spectroscopy has been applied to study the atomic hyperfine structure of thulium (Tm, $Z = 69$) isotopes, leading towards the proton emitter ^{147}Tm , a nucleus recently confirmed to exhibit triaxial deformation in both its ground and isomeric states [1]. Tm possesses a single stable isotope, ^{169}Tm , with ground-state electronic configuration $[\text{Xe}] 4f^{13} 6s^2$ and a first ionization potential of 6.184 eV [2], giving rise to a rich and complex atomic spectrum that is well-suited to two-step resonance laser ionization. This technique provides information about nuclear magnetic dipole moments and changes in mean-square charge radii via hyperfine structure and isotope shift measurements of stable ^{169}Tm [3].

Offline laser spectroscopy measurements of ^{169}Tm were performed at the Atomic Beam Unit (ABU), where new two-step laser excitation schemes were developed and tested, and the discovery of a new autoionizing (AI) state was identified, offering a significant enhancement in ionization efficiency for future online experiments. The status of the data analysis from these measurements will be presented.

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