EGAS 54

Book of abstracts

June 20, 2023

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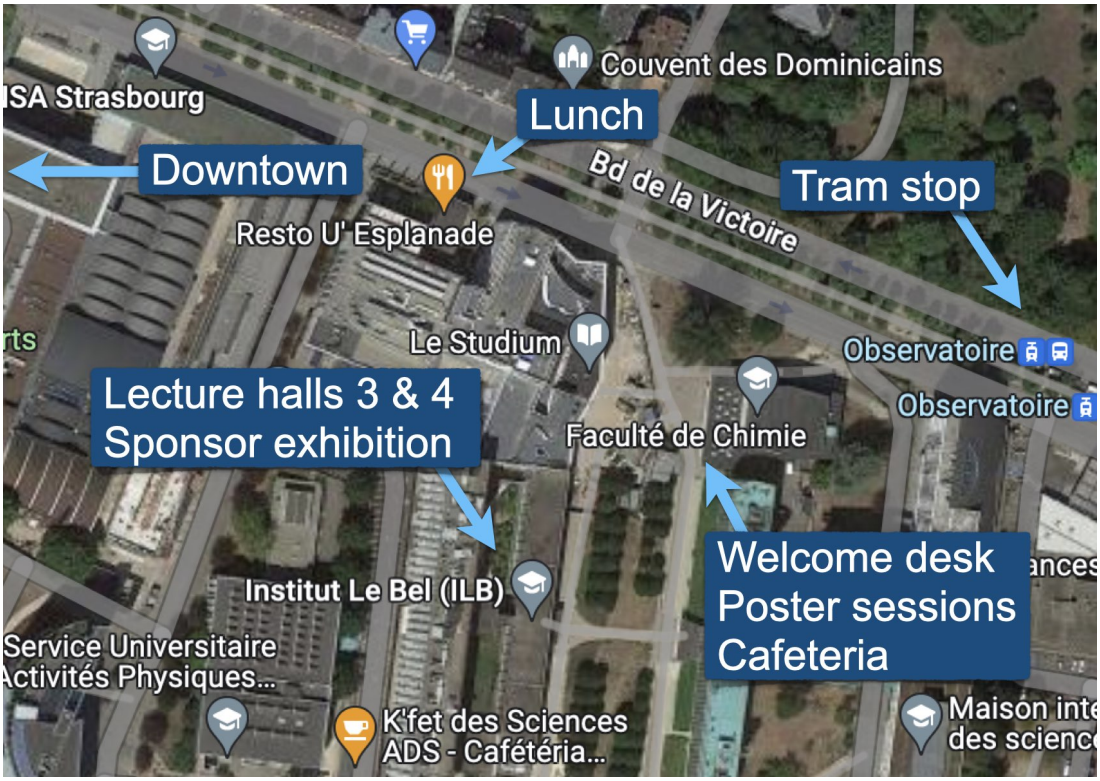
PRACTICAL INFORMATION

- All talks take place in lecture halls 3 & 4 of the Institut Le Bel.
- The sponsor exhibition can be found just in front of the lecture halls in Institut Le Bel.
- The Welcome desk and the Cafeteria is 50m across at the Faculté de Chimie.
- All poster sessions and the welcome reception take place at the Faculté de Chimie.



PLENARY TALKS

Monday 9:00–9:45	**Kardar-Parisi-Zhang universal scaling in the coherence of polariton condensates** Jacqueline Bloch
Monday 9:45–10:30	**Full quantum control of ultracold polar molecules** Simon L. Cornish
Tuesday 9:00–9:45	**New platforms for quantum science: ultracold molecules, and highly magnetic atoms** Wolfgang Ketterle
Tuesday 9:45–10:30	**Quantum optics with cold atoms trapped along nanowaveguides** Julien Laurat
Tuesday 2:00–3:00	**100 years after de Broglie: A bold hypothesis at the start of universal matter-wave Interferometry** Markus Arndt
Wednesday 9:30–10:15	**Protein structure and dynamics using X-ray free-electron lasers – pitfalls** Ilme Schlichting
Thursday 9:00–9:45	**Exploring new scientific frontiers using programmable atom arrays** Mikhail Lukin
Thursday 9:45–10:30	**A molecular bond between ions and Rydberg atoms** Tilman Pfau
Thursday 11:15–12:00	**Towards clocks at frequencies beyond the optical range** José R. Crespo López-Urrutia
Thursday 12:00–12:45	**Exploring Large-Scale Entanglement in Quantum Simulation** Peter Zoller

PUBLIC LECTURES

Monday 4:00–4:45	**The Alchemy of Vacuum** Thomas W. Ebbesen
Monday 4:45–5:30	**Nonenzymatic Metabolic Reactions and Life's Origins** Joseph Moran

INVITED TALKS

Monday 11:10–11:40 (ITD)	**Quantum diamond magnetometry at extreme pressures** Jean-François Roch
Monday 11:10–11:40 (ITD)	**Sub-symmetry protected topological states** Hrvoje Buljan
Monday 2:00–2:30 (B.I)	**Engineering of many-body states in a driven-dissipative cavity QED system** Tobias Donner
Monday 2:00–2:30 (F.I)	**Precision molecular spectroscopy using optical frequency combs** Aleksandra Foltynowicz Matyba
Tuesday 11:10–11:40 (C.I)	**High accuracy predictions of properties of heavy atoms and molecules and evaluation of uncertainties** Anastasia Borschevsky
Wednesday 11:20–11:50 (C.II)	**Challenging QED with atomic Hydrogen** Thomas Udem
Wednesday 11:20–11:50 (A.II)	**Topology in orbital bosonic systems** Verònica Ahufinger
Wednesday 2:00–2:30 (ITD)	**Fractal ground state, spectral properties, and quantum dynamics of one-dimensional Wigner crystals in periodic potentials** Giovanna Morigi
Wednesday 2:00–2:30 (B.II)	**Higgs excitation branch in Fermi superfluids** Yvan Castin
Wednesday 4:00–4:30 (F.II)	**Attosecond spectroscopy of the electronic and vibrational dynamics in Furan** Jens Biegert
Wednesday 4:00–4:30 (ITD)	**Towards cold and controlled reactive collisions** Jolijn Onvlee
Thursday 2:00–2:30 (D.I)	**Quantum Technology, Quantum Simulations, and Precision Measurements with Ultracold Strontium** Sebastian Blatt
Thursday 2:00–2:30 (D.II)	**Optical Traps for Ions & Ultracold Atoms** Tobias Schätz

Thursday 2:30–3:00 (D.I)	**Quantum simulation of the dipolar XY model using Rydberg atom arrays** Thierry Lahaye
Thursday 2:30–3:00 (D.II)	**Coherence of light from ensembles of many independent atoms** Lukáš Slodička
Thursday 4:00–4:30 (D.III)	**From atoms and light to digital quantum computing** Shannon Whitlock
Thursday 4:00–4:30 (D.IV)	**Observing Spin-Squeezed States under Spin-Exchange Collisions for a Second** Jakob Reichel
Thursday 4:30–5:00 (D.III)	**Ultracold atoms in ring traps: from fundamentals to atomtronics applications** Anna Minguzzi

CONTRIBUTED TALKS

Monday 11:40–12:00 (ITD)	**Long spin and optical coherence times of Er sites in Si (G.1)** Alexey Lyasota
Monday 11:40–12:00 (ITD)	**Steering edge currents through a Floquet topological insulator (C.1)** Helena Drüeke
Monday 12:00–12:20 (ITD)	**Strong dual dressing of a Rb qubit (B.1)** Andrea Fioretti
Monday 12:00–12:20 (ITD)	**Tailoring photon statistics with an atom-based two-photon interferometer (B.2)** Maximilian Schemmer
Monday 2:30–2:50 (B.I)	**A hybrid quantum system of ultracold polar molecules and Rydberg atoms (B.3)** Daniel Ruttley
Monday 2:30–2:50 (F.I)	**Precision Spectroscopy of highly charged ions with sub-Hz uncertainty (F.1)** Malte Wehrheim
Monday 2:50–3:10 (B.I)	**Tunable long-distance mediated interactions in quantum simulators with cold atoms (B.4)** Javier Arguello-Luengo
Monday 2:50–3:10 (F.I)	**Frequency-comb-driven atom interferometry (F.2)** Cyrille Solaro
Tuesday 11:10–11:40 (A.I)	**Microscopically-controlled arrays of alkaline-earth atoms (A.1)** Nelson Darkwah Oppong
Tuesday 11:40–12:00 (A.I)	**Cavity-QED Quantum Simulator of Random Spin Models (A.2)** Francesca Orsi
Tuesday 11:40–12:00 (C.I)	**AION: A UK collaboration searching for gravitational waves and dark matter with a large-baseline differential atom interferometer (C.2)** Charles Baynham
Tuesday 12:00–12:20 (A.I)	**Dark state transport in a strongly interacting fermi gas (A.3)** Mohsen Talebi
Tuesday 12:00–12:20 (C.I)	**Searching for ultralight dark matter with $^{171}Yb^{+}$ clocks (C.3)** Nils Huntemann

Wednesday 11:50–12:10 (C.II)	**Upcoming atomic physics studies of ion-ion collisions (E.1)** Mariette Jolly
Wednesday 11:50–12:10 (A.II)	**Self-Pinning Transition of impurities in a Bose-Einstein Condensate (A.4)** Thomas Busch
Wednesday 12:10–12:30 (C.II)	**Tunneling measured in a very slow ion-molecule reaction (C.4)** Robert Wild
Wednesday 12:10–12:30 (A.II)	**Melting of a vortex lattice in a fast rotating Bose gas (A.5)** Hélène Perrin
Wednesday 2:30–2:50 (ITD)	**Polarons and their mediated interactions in Fermi-Bose and Fermi-Fermi mixtures of Li and K (A.6)** Cosetta Baroni
Wednesday 2:30–2:50 (B.II)	**Spin squeezing of dipoles enhanced by mobility (F.3)** David Wellnitz
Wednesday 2:50–3:10 (ITD)	**The Frustration of Being Odd (C.5)** Fabio Franchini
Wednesday 2:50–3:10 (B.II)	**Interfacing Rydberg atoms with superconducting microwave circuits - state control and tunability (B.5)** Luke Brown
Wednesday 4:30–4:50 (F.II)	**Quantum enhanced ultra high sensitivity gravi-gradiometer (F.4)** Valentin Cambier
Wednesday 4:30–4:50 (ITD)	**Trapped ions in an ultracold gas: buffer gas cooling and chemical reactions (B.6)** Eleanor Trimby
Wednesday 4:50–5:10 (F.II)	**Enhancement in multiphoton absorption measurements with squeezed light (B.7)** Shahram Panahiyan
Wednesday 4:50–5:10 (ITD)	**An interaction-driven Otto heat engine using a harmonically trapped Lieb-Liniger gas (A.7)** Karen Kherunstsayn
Thursday 3:00–3:20 (D.I)	**Interacting Laser-Trapped Circular Rydberg Atoms (D.1)** Clement Sayrin
Thursday 3:00–3:20 (D.II)	**Spin-squeezed states with ultracold fermions (A.8)** Mažena Mackoit-Sinkevičienė

Thursday 4:30–4:50 (D.IV)	**Multi-parameter quantum sensing and magnetic communications with a hybrid dc/rf optically-pumped magnetometer (D.2)** Aleksandra Sierant
Thursday 5:00–5:20 (D.III)	**Fractional angular momentum quantization in Atomtronic circuits (A.9)** Juan Polo
Thursday 4:50–5:10 (D.IV)	**Detecting of high-dimensional entanglement with quantum gas microscopes (B.8)** Martin Gärttner

POSTERS

SESSION I (Monday 6:00–8:00)

C.1 **Three interacting particles in a circular trap: periodic trajectories and bifurcations**
Benoît Zumer

C.2 **Interference dynamics of matter-waves of SU(N) fermions**
Wayne Jordan Chetcuti

C.3 **Spectral Properties of Quantum Graphs and Microwave Networks**
Omer Farooq

C.4 **Zeeman-Sisyphus Deceleration of CaF**
Bethan Humphreys

C.5 **Relative dynamics of quantum vortices and massive cores in binary BECs**
Alice Bellettini

C.6 **Towards a High-Precision Atomic Mass Measurement of the ^{3}He Nucleus at LIONTRAP**
Olesia Bezrodnova

C.7 **On-demand control of g(2) correlations of photon emission using interfering modes in collectively interacting emitters**
Deepak Aditya Suresh

C.8 **ALPHATRAP: High-precision single-ion measurements in a Penning Trap**
Jonathan Morgner

C.9 **Resonant X-ray scattering by highly-charged ions exposed to magnetic fields**
Jan Richter

C.10 **Polarization Phenomena of Photonic Processes in the Hard X-Ray Regime Revealed by Compton Polarimetry**
Tobias Over

C.11 **Theoretical study of spin polarization in multiphoton ionization of Xe**
Anton Artemyev

C.12 **Full relativistic electronic structure calculations of TlCl for laser cooling experiment**
Xiang Yuan

C.13 **Lifetimes of excited states of the lanthanum negative ion**
Dan Gibson

C.14 **Extension of Judd-Ofelt theory: Application on trivalent Eu, Nd and Er**
Gohar Hovhannesyan

C.15 **Molecular-frame photoelectron circular dichroism of O 1s-photoelectrons of trifluoromethyloxirane**
Nikolay Novikovskiy

C.16 **The most condense material in the Universe; 10^{25} times of a black hole (Cidtonium)**
Gh. Saleh

C.17 **A New Explanation for How Black Holes Are Created and Their Types**
Gh. Saleh

C.18 **A polyatomic molecular cryogenic buffer gas beam for tabletop precision experiments**
Ties Fikkers

C.19 **Quadratic Zeeman effect in light three-particle systems**
Petar Danev

C.20 **High-resolution mid-infrared molecular spectroscopy with cold molecules for fundamental tests**
Marylise Saffre

C.21 **Elastic scattering of twisted electron wave packets by crystals**
Sophia Strnat

C.22 **Manipulation of Impurities in a Fermi Sea with Raman Transitions**
Erich Dobler

C.23 **Influence of the saturation effect on the Zeeman and hfs spectra**
Łukasz Sobolewski

C.24 **Accurate molecular ab initio calculations in support of strong-field attosecond physics experiments**
Giorgio Visentin

C.25 **Phase-space measurements of a buffer gas cooled BaF beam for the NL-eEDM experiment**
Maarten Mooij

C.26 **A Global Approximation Interpretation of Quantum Mechanics**
Yian Lei

C.27 **Spectral properties of four-wave mixing in the four-level atomic system**
Thi-Thuy Nguyen

C.28 **Single- and double-ionization processes of antiproton-helium and antiproton-molecular hydrogen collisions in the keV energy range**
Congcong Jia

C.29 **Heat rectification in ion crystals**
Marisa Pons

C.30 **Probing properties of twisted light by the Hanle effect**
Riaan Philipp Schmidt

C.31 **Compton Polarimetry on Rayleigh Scattering of Highly Linearly Polarized Hard X-Rays on Gold Atoms**
Wilko Middents

C.32 **Theory of the magnetic moments and hyperfine splitting of ^{3}He**
Bastian Sikora

C.33 **3D quantum model of the photon**
Rita Veilande

C.34 **Nondipole-Induced Asymmetry in the Angular Distribution of Photoelectrons from Fixed-in-Space CO Molecules**
Dmitrii Rezvan

C.35 **Collective frequency shift of scattering off three-dimensional optical lattices**
Shengnan Zhang

C.36 **Towards a limit on the electron's electric dipole moment using BaF**
Joost van Hofslot

C.37 **Ionization, total and state selective charge exchange cross sections in fusion related collision systems – Significant improvement in the classical treatment of one-electron atomic systems with the addition of the Heisenberg correction**
Károly Tőkési

C.38 **Coulomb corrections to Delbrück scattering above the pair production threshold**
Jonas Sommerfeldt

C.39 **Probing Casimir-Polder Rydberg-Surface Interactions: Towards Extreme Near-Field Measurements**
Biplab Dutta

E.1 **Multi-Platform Atomic Data Calculations in Re III, IV, V: Application to Nuclear Fusion Research**
Sébastien Gamrath

E.2 **Two-photon- and magnetic dipole one-photon absorption in atomic iodine for temperature and atomic density diagnostics in low-temperature plasmas and a revision of the energy levels of I I**
Christophe Blondel

E.3 **Protein structure and dynamics using X-ray free-electron lasers - pitfalls**
Ilme Schlichting

E.4 **Theoretical study of iodine ion-ion collisions in the context of spacecraft propulsion**
Sylvain Badin

E.5 **Progress in polarization of ^{3}He atoms in a magnetized plasma (PAMP)**
Geneviève Tastevin

E.6 **The role of the 3 → 5 excitation channels in the dielectronic recombination of M- shell Fe ions: the Na and Mg isoelectronic sequences**
Giorgio Visentin

E.7 **Determination of mercury in wild bird samples by Zeeman atomic absorption spectrometry**
Rita Veilande

E.8 **Numerical Studies of the Impact of Electromagnetic Field of Radiation on Valine**
Teodora Kirova

E.9 **DESIREE: Mutual neutralization experiments**
Henning Schmidt

E.10 **Magneto-optical filters using atomic filters: from Hamiltonian to application**
Danielle Pizzey

E.11 **Determination of the radiative properties of Ta VII using a multiplatform approach**
Patrick Palmeri

E.12 **Expansion and line-binned opacities of samarium ions for the analysis of early kilonova emission from neutron star mergers**
Patrick Palmeri

E.13 **Atomic data and expansion opacity calculations in two representative 4d transition elements, niobium and silver, for the spectral analysis of kilonovae**
Patrick Palmeri

E.14 **Influence of rotational and collision energy on the reaction rate of the D_2^++NH_3 reaction**
Raphaël Hahn

F.1 **Ramsey interferometry with optimally twisted states and measurements**
Maja Scharnagl

F.2 **Planetary states of the Sr atom**
Matthieu Génévriez

F.3 **Ultrafast electro-optic fractional Fourier imaging at the single-photon level**
Michał Lipka

F.4 **Polarization dynamics in an alkali-noble gas comagnetometer**
Emmanuel Klinger

F.5 **Rb microfabricated cells for a two-photon optical frequency reference**
Emmanuel Klinger

F.6 **Excitation mechanisms for the ^{229}Th isomer**
Tobias Kirschbaum

F.7 **Accurate bootstrapping of an optical frequency comb to the REFIMEVE 1542 nm reference**
Rodolphe Le Targat

F.8 **Ten quectonewton local force sensor with atom interferometry**
Yann Balland

F.9 **Diatomic molecular vibrations in a strong infrared laser field: an analytic treatment of the laser-dressed Morse potential**
Szabolcs Hack

F.10 **Quantum interference in strong-field ionization by a linearly polarized laser pulse solves the problem of non-zero tunnel exit momentum**
Szabolcs Hack

F.11 **High-resolution probing of sub-wavelength confined molecules**
Hippolyte Mouhanna

F.12 **Collision-induced 2^3P-1^1S excitation transfer in helium discharges: assessment and implications for ^{3}He MEOP**
Pierre-Jean Nacher

F.13 **Designing potentials with Laguerre-Gaussian modes for systematic effects characterization below 10^{-18} level in strontium optical lattice clocks**
Miguel Angel Cifuentes Marin

F.14 **Precision spectroscopy of transitions from the metastable 2 ^{3}S$_1$ state of ^{4}He to high-np Rydberg states**
Gloria Clausen

F.15 **Comb-assisted Lamb-dip spectroscopy of mercury atoms at 253.7 nm**
Stefania Gravina

F.16 **A comb-locked frequency chain for precision mercury spectroscopy and temperature metrology**
Naveed Ahmed Chishti

F.17 **Strontium tweezer arrays for precision measurements**
Matthew Hill

F.18 **High-resolution mid-infrared molecular spectroscopy for precision measurements and tests of fundamental physics**
Mathieu Manceau

F.19 **Nonlinear pulse compression in a gas-filled multipass cell**
Prachi Nagpal

F.20 **Laser spectroscopy of Iodine molecule in the 14400-14710 cm^{-1} range**
Manuel Alejandro Lefran Torres

F.21 **Complete reconstruction of ultrashort laser pulses by convolutional neural networks**
Istvan-Ferenc Toth

F.22 **An efficient Zeeman slower for the ROYMAGE transportable Ytterbium clock**
Jesus Romero Gonzalez

F.23 **High-resolution spectroscopy of the ground and low-lying excited states of MgKr$^+$ and MgXe$^+$**
Carla Kreis

F.24 **Rovibrational and Hyperfine Structure of the Molecular Hydrogen Ion from Spectroscopy of Rydberg-Stark Manifolds**
Ioana Doran

F.25 **Lamb-dip cavity ring-down spectroscopy of acetylene at 1.4 μm**
Muhammad Asad Khan

F.26 **Coherent Laser Spectroscopy on Potassium D2 Line for Magnetometry Applications**
Stoyan Tsvetkov

F.27 **The ℓ-dependence of the autoionization rates of core-excited Rydberg states**
Eduardo Marin Bujedo

F.28 **Self-Oscillations in a Strongly-Driven Thermal Vapor with Rydberg Interactions**
Karen Wadenpfuhl

F.29 **Performing high precision spectroscopy on ultracold ammonia molecules in an electrostatic trap**
Wander van der Meer

F.30 **Current status of the Al$^+$ ion clock at PTB**
Marek Hild

F.31 **Magnetically induced transitions for extension of frequency reference from IR to UV**
Ara Tonoyan

F.32 **PFI-ZEKE characterization of the ground and low-lying excited states of MgO$^+$**
Carla Kreis

F.33 **Investigation of the interplay pumping mechanisms of SiCMOS charge pumps under conditions of elevated temperature and power applied**
Steve Yianni

F.34 **Quantum-enhanced multiparameter estimation and compressed sensing of a field**
Baamara Youcef

F.35 **Sub-Doppler spectroscopy of ^{39}K for magnetic field measurements**
Rodolphe Momier

F.36 **Formation of strongly frequency-shifted EIT resonances using "forbidden" transitions of Cesium**
Rodolphe Momier

F.37 **Photoelectron Circular Dichroism of fenchone induced by broadband laser pulses**
Eric Kutscher

F.38 **Progress on a ^{171}Yb active optical clock based on superradiance**
Francisco Ponciano Ojeda

G.1 **Laser cooling and shuttling of trapped ions in strongly inhomogeneous magnetic fields**
Yanning Yin

G.2 **Information-theoretical analysis of Dirac and non-relativistic quantum oscillators**
Iván López-García

G.3 **Time Dilation and Relativistic Blueshift in Photoionization of Atoms**
Johanne Elise Vembe

G.4 **Experimental determination of the energy dependence of the rate of the muon transfer reaction from muonic hydrogen to oxygen for collision energies up to 0.1 eV**
Dimitar Bakalov

G.5 **Electronic Structure of the Rydberg Molecule He-ND_3**
Pablo Fernández-Mayo

G.6 **Rovibrational dynamics of Rb_2 in a high intensity optical centrifuge**
Juan Manuel García-Garrido

B.1 **Quantum Optics with thermal vapours in the hyperfine Paschen-Back regime**
Clare Higgins

B.44 **Optimized tomography of a complex collective quantum state**
Szymon Pustelny

D.1 **Short-range interactions generating massive multipartite entanglement for metrology**
Tommaso Roscilde

SESSION II (Wednesday 5:30–7:30)

A.1 **Many to few: From ultracold plasma to atom-ion hybrid systems**
Jette Heyer

A.2 **Coherence of confined matter in lattice gauge theories at the mesoscopic scale**
Enrico Calogero Domanti

A.3 **Density and pseudo-spin rotons in a bilayer of Rydberg-dressed bosons**
Bilal Tanatar

A.4 **Optically trapped DyK Feshbach molecules near quantum degeneracy**
Zhuxiong Ye

A.5 **Beyond universality in repulsive SU(N) Fermi gases**
Jordi Pera

A.6 **All optical switching in a three-level V-type atomic medium based on electromagnetically induced transparency**
Nguyen Thi Thu Hien

A.7 **Making statistics work: a quantum engine in the BEC-BCS crossover**
Keerthy Menon

A.8 **Self-Pinning Transition of impurities in a Bose-Einstein Condensate**
Thomas Busch

A.9 **Realization of an atomic quantum Hall system in four dimensions**
Jean-Baptiste Bouhiron

A.10 **Production of a $v_X = 0$ Rb_2 supersonic beam by optical pumping**
Manuel Alejandro Lefran Torres

A.11 **Quantum Aubry transition in chains of long-range interacting particles**
Raphaël Menu

A.12 **Expansion of a quantum gas onto the curved surface of an ellipsoid**
Laurent Longchambon

A.13 **Preparing spin textures of SU(N) Fermions in optical lattices**
Husain Ahmed

A.14 **A new Lithium 6 Quantum Gas Microscope: Exploring the Projection of a Many-Body Wavefunction into Single Atoms**
Joris Verstraten

A.15 **Vortex Pair Dynamics in Three-Dimensional Homogeneous Dipolar Superfluids**
Srivatsa Prasad

A.16 **Precision measurement of atom-dimer interaction in a uniform planar Bose gas**
Guillaume Chauveau

A.17 **Dark states potentials and bands for ultra cold atoms**
Mateusz Łącki

A.18 **Subradiance in ordered ensembles of Dysprosium atoms**
Britton Hofer

A.19 **Ionic polarons and bipolarons in an ultracold Bose gas**
Krzysztof Jachymski

A.20 **Brillouin spectroscopy of metastable superfluid helium-4**
Jules Grucker

A.21 **Bose-Hubbard triangular ladder in an artificial gauge field**
Catalin-Mihai Halati

A.22 **Self-bound Fermi-Fermi mixtures in 1D**
Andrea Tononi

A.23 **Thermal fading of the $1/k^4$-tail of the momentum distribution induced by the hole anomaly**
Giulia De Rosi

A.24 **Optically induced lattices in rubidium vapor**
Vjekoslav Vulić

A.25 **Self-binding in one- and two-dimensional mass-imbalanced fermionic mixtures**
Jules Givois

A.26 **Binary supersolids in dipolar condensate mixtures**
Russell Bisset

A.27 **A Multipurpose Lithium-6 Platform for Analog Quantum Simulation**
Tim de Jongh

A.28 **Sensing interactions in atomic quantum systems**
Rianne Lous

A.29 **State-selective charge exchange in ion-molecule and three-body recombination in ion-atom-atom rubidium systems at the ultracold temperatures**
Amrendra Pandey

A.30 **Cavity-assisted dispersive interaction of cold atoms with a frequency comb**
Ticijana Ban

A.31 **Charge and pair density waves induced by light in a strongly interacting Fermi gas**
Tabea Bühler

A.32 **Imaging of individual ions via Stark shift-induced photoabsorption**
Thibault Vogt

B.2 **Sideband Thermometry on Ion Crystals**
Ivan Vybornyi

B.3 **Multiple polaritonic edge states in a Su-Schrieffer-Heeger chain strongly coupled to a multimode photonic cavity**
Guillaume Weick

B.4 **Disorder-enhanced transport in a chain of lossy dipoles strongly coupled to cavity photons**
Thomas Allard

B.5 **X-ray Waveguide QED with Mössbauer Nuclei**
Petar Andrejic

B.6 **Non-local Multi-qubit Quantum Gates and Entanglement Generation in Cavity**
Vineesha Srivastava

B.7 **Optical tweezers in trapped-ion quantum simulations**
Clara Robalo Pereira

B.8 **Higher-order mean-field theory of chiral waveguide QED**
Kasper Jan Kusmierek

B.9 **Azimuthal Dependence of Electromagnetically Induced Grating in a Double V-type Atomic System near Plasmonic Nanostructure**
Teodora Kirova

B.10 **Robustness of different modifications of the quantum random walk search algorithm**
Hristo Tonchev

B.11 **Quantum Gate Optimization for Rydberg Architectures in the Weak-Coupling Limit**
Nicolas Heimann

B.12 **Hilbert Space Engineering of Nuclear Spin Qudits**
Jean-Gabriel Hartmann

B.13 **Towards realization of long-lived chains of circular Rydberg atoms for quantum simulation**
Ankul Prajapati

B.14 **Deterministic Wigner-negative photonic qubits (from an intracavity Rydberg superatom)**
Sébastien Garcia

B.15 **Second-scale rotational coherence in a gas of ultracold polar molecules**
Luke Fernley

B.16 **Correlated insulator and supersolid phases in a one-dimensional $\mathbf{Z}_2$ lattice gauge theory**
Vaibhav Sharma

B.17 **Molecular photoionization time delays. A full-dimensional study**
Adrián Jesús Suñer Rubio

B.18 **Dynamical phases in an atom-cavity system**
Hans Kessler

B.19 **Characterizing Operator Growth in Disordered Quantum Spin Chains via Out-of-Time-Ordered Correlators**
Maximilian Klaus Müllenbach

B.20 **The Quantum Wigner-Smith Operator: Micromanipulation, Metrology and Vacuum Forces**
Lukas Rachbauer

B.21 **Optimal control of Bose-Einstein condensates in an optical lattice**
Juliette Billy

B.22 **Noisy qudits vs qubits : Conditions on Gate Efficiency**
Denis Jankovic

B.23 **Tweezers arrays of erbium atoms for quantum simulation**
Antonio Ortu

B.24 **Scalable spin squeezing in a dipolar Rydberg atom array**
Jamie Boyd

B.25 **On-demand control of g(2) correlations of photon emission using interfering modes in collectively interacting emitters**
Deepak Aditya Suresh

B.26 **Certification of quantumness in the prepare-and-measure scenario**
István Márton

B.27 **Investigation of the dipole moment of 6,11-dihydroxy-5,12-naph -thacenedione using molecular diffraction**
Richard Ferstl

B.28 **Dipolar XY Magnets in a Two-dimensional Rydberg Array**
Cheng Chen

B.29 **QRydDemo: A 500-qubit quantum computer demonstrator using the Sr fine-structure qubit**
Govind Unnikrishnan

B.30 **Reconstruction of the open quantum system with multiple isolated Random Telegraph Noise sources**
Georgii Semin

B.31 **Dual-type Dual-element Atom Array for Quantum Computation and Simulation**
Wenchao Xu

B.32 **Spatially Dependent Light Amplification Without Inversion**
Hamid Reza Hamedi

B.33 **Rise and fall, and slow rise again, of operator entanglement under dephasing**
Guillermo Javier Preisser Beltrán

B.34 **Towards long effective-time evolution of 2D fluids of light in propagating geometries**
Ruggero Giampaoli

B.35 **Controlled flow of excitations in a ring-shaped network of Rydberg atoms**
Francesco Perciavalle

B.36 **Exploring molecular properties using far-field matter-wave diffraction**
Ksenija Simonović

B.37 **High-speed Interleaved SNSPDs with nanosecond scale gating option**
Antonio Guardiani

B.38 **Trapping-Arrays of interacting Circular Rydberg Atoms**
Andres Duran Hernandez

B.39 **Multifractality in the interacting disordered Tavis-Cummings model**
Francesco Mattiotti

B.40 **Towards the control of temporal entangled single-photon pulses in the presence of magnetic field**
Anahit Gogyan

B.41 **FermiQP - A Fermion Quantum Processor**
Robin Groth

B.42 **A cryogenic neutral atom optical tweezer array**
Matteo Marinelli

B.43 **Rydberg quantum simulator using strontium atoms in tweezers**
Ivo Knottnerus

D.2 **Dynamics of a coupled Ion-Nanowire Hybrid System**
Moritz Weegen

D.3 **Quantum rotation sensor with real-time readout based on an atom-cavity system**
Jim Skulte

D.4 **Frustrating quantum batteries**
Alberto Giuseppe Catalano

D.5 **Evolutionary shaping of leakage-aware pulses for Rydberg blockade gates**
Tam'si Ley

D.6 **Generating multiparticle entangled states by self-organization of driven ultracold atoms**
Ivor Kresic

D.7 **Optimizing Rydberg Gates for Logical Qubit Performance**
Sven Jandura

D.8 **Development of an atomic magnetometer for space-borne biomagnetic measurements**
Victor Lebedev

D.9 **Observation of quantum correlations on the strontium optical clock transition**
Haosen Shang

D.10 **Multidirectional magnetic field sensing using ground-state aligment in atomic Cs**
Arturs Mozers

D.11 **Isolated Core Excitation: a new tool for the manipulation of quantum information with divalent Rydberg atoms**
Steven Lepoutre

D.12 **A comparative study of decoherence rates in alkali cells for applications in quantum memories**
Marin Đujić

D.13 **Enhancing Atom-Photon and Atom-Atom Interactions with Integrated Nanophotonics**
Annika Belz

D.14 **Phase and frequency stabilization of diode lasers**
Sayali Shevate

D.15 **A dual-atom interferometer for precision inertial sensing**
Swarup Das

D.16 **Robust control and optimal Rydberg states for neutral atom two-qubit gates**
Madhav Mohan

PLENARY TALKS

Kardar-Parisi-Zhang universal scaling in the coherence of polariton condensates

Jacqueline Bloch

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The Kardar–Parisi–Zhang (KPZ) equation [1], originally derived to describe the kinetic roughening of growing interfaces is a stochastic non-linear differential equation that applies to a large class of non-equilibrium systems, ranging from the growth of nematic liquid crystal clusters, of bacterial colonies, or the propagation of a combustion front. The shape of such an interface $h(\mathbf{r},t)$ is described by the following stochastic equation:

$$\partial_t h = \nu\nabla^2 h + \frac{\lambda}{2}(\nabla h)^2 + \eta \tag{1}$$

where the first term is a smoothening diffusion, the second term is a crucial nonlinear contribution that leads to critical roughening of the interface and η is a Gaussian noise. Interestingly the spatial and temporal correlation functions of $h(\mathbf{r},t)$ show **universal scaling laws**, with critical exponents that only depend on the dimensionality whatever the system.

Recently, it was discovered that the phase dynamics in the coherent emission of out of equilibrium condensates of light (named polariton condensates) also obeys the celebrated KPZ equation [2-4]. Interestingly, since the phase is a compact variable, periodically defined between 0 and 2π **the physics is enriched by the possible emergence of vortices**. Actually even in 1D, where usually vortices are excluded, exotic spatio-temporel vortices have been predicted to play a role [5].

In the present talk, after a general introduction to the system, I will explain how we could generate extended 1D polariton condensates [6] and probe their first order coherence. We demonstrate that the decay of the first order coherence in space and time indeed presents universal scaling laws characteristic for the KPZ universality class in 1D [7]. The influence of vortices in these experiments will be discussed.

Our work highlight the profound difference between driven-dissipative out of equilibrium condensates and their equilibrium counterparts [8]. We anticipate that this physics should also be relevant in extended vertical cavity lasers.

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Full quantum control of ultracold polar molecules

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Ultracold polar molecules are an exciting new platform for quantum science and technology. The combination of rich internal structure of vibration and rotation, controllable long-range dipole-dipole interactions and strong coupling to applied electric and microwave fields has inspired many applications. These include quantum simulation of strongly interacting many-body systems, the study of quantum magnetism, quantum metrology and molecular clocks, quantum computation, precision tests of fundamental physics and the exploration of ultracold chemistry. Many of these applications require full quantum control of both the internal and motional degrees of freedom of the molecule. In Durham, we study ultracold ground-state RbCs molecules formed by associating Rb and Cs atoms using a combination of magnetoassociation and stimulated Raman adiabatic passage (STIRAP) [1]. This talk will report our work on the development of full quantum control of the molecules. Specifically, we will discuss how we have mastered the ac Stark shift due to the trapping light [2] to demonstrate robust storage qubits in the molecule [3] and will describe the development of magic traps [4] that support second-scale rotational coherences giving access to controllable dipole-dipole interactions [5]. Finally, we will describe new experiments that produce single molecules in optical tweezers starting from a single Rb and a single Cs atom [6]. Using this platform, we prepare the molecules in the motional ground state of the trap and can perform addressing and detection of single molecules [7,8].

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New platforms for quantum science: ultracold molecules, and highly magnetic atoms

Wolfgang Ketterle

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Ultracold atoms and molecules continue to provide new opportunities for basic quantum science, for precision measurement, and for the study of paradigmatic Hamiltonians, called quantum simulations. I will illustrate two novel systems: Using ultracold NaLi atoms in the triplet ground state, we were able to control chemistry via magnetic fields and quantum interference. Using a new optical super-resolution technique, we could localize dysprosium atoms with a separation much smaller than the diffraction limit of light, down to 50 nm, and observe strong purely magnetic interactions between atoms which are usually much weaker than electric interactions.

Quantum optics with cold atoms trapped along nanowaveguides

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Considerable efforts have been recently devoted to combining ultracold atoms and nanophotonic devices to obtain not only better scalability and figures of merit than in free-space implementations, but also new paradigms for atom-photon interactions. Dielectric waveguides offer a promising platform for such integration because they enable tight transverse confinement of the propagating light, strong photon-atom coupling in single-pass configurations and potentially long-range atom-atom interactions mediated by the guided photons.

In the talk, I will present our efforts in this emerging neutral-atom waveguide-QED field of research. Using nanofiber trapped atoms, we demonstrated the capability to herald, store and read out a single collective excitation that is preferentially coupled to the guided mode. In this nanofiber setting, using a dynamically-controlled Bragg configuration, we also recently pushed the non-linearity down to the few-photon level. I will then describe our works towards stronger coupling in single pass by using photonic-crystal slow-mode waveguides with engineered dispersion. Localizing and trapping atoms in the proximity is a strong challenge and I will describe how novel structures and optical techniques can be used.

100 years after de Broglie: A bold hypothesis at the start of universal matter-wave Interferometry

Markus Arndt

University of Vienna, Faculty of Physics & Vienna Doctoral School in Physics

When Louis de Broglie proposed the concept of matter waves in 1923, he claimed that it was likely to 'solve all problems related to quanta'. His idea inspired Schrödinger's wave equation and became the basis for a century of quantum technologies. By now, the quantum wave nature of matter is an integral part of quantum chemistry and it has been applied with free electrons, neutrons or atoms or even large esembles of quantum degenerate atoms, in refined applications from materials research to precision measurements of inertial forces or fundamental constants.

All experiments so far have confirmed quantum mechanics to be correct and precise. And yet, one may even claim that de Broglie's idea gave birth to just another big intellectual challenge: Why is our daily life so normal? How does quanutm mechanics interface to the classical world? Why don't we see macroscopic objects in delocalized and superposed states? This question has inspired our experiments in Vienna to develop universal matter-wave interferometry, i.e. technologies that can study the quantum wave nature of atoms or molecules, vitamins or polypeptides, clusters of atoms or clusters molecules. I will describe ongoing explorations to expand these studies to objects of increasing mass and complexity and I will give an outlook into the breadth of current efforts to probe the macroscopicity of quantum mechanics.

Protein structure and dynamics using X-ray free-electron lasers - pitfalls

Ilme Schlichting

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X-ray crystallography has tremendous impact on biology, having yielded the structures of thousands of proteins and given detailed insight into their working mechanisms. The requirement for macroscopic crystals, which can be difficult to obtain, as well as the often severe radiation damage caused by the ionizing X-rays during data acquisition - in particular when using small crystals - has been relieved with the advent of X-ray free-electron lasers (XFELs). With their highly brilliant short X-ray pulses XFELs enable room temperature measurements, allowing to perform time-resolved experiments at atomic resolution at the chemical timescale of femtoseconds. More than ten years have passed since the Linac Coherent Light Source opened its doors to users. Since then a great deal of technical development has taken place, allowing to gain new scientific insight. More XFEL facilities have come online, including the first MHz facility. Time to reflect on lessons learned, pitfalls, and to think about future challenges. The talk focusses on pump probe experiments.

Exploring new scientific frontiers using programmable atom arrays

Mikhail Lukin

Department of Physics, Harvard University

We will discuss the recent advances involving programmable, coherent manipulation of quantum systems based on neutral atom arrays excited into Rydberg states, allowing the control over several hundred qubits in two dimensions. Recent developments involving both analog and digital quantum simulations and quantum information processing will be described. In particular, the realization of novel quantum processing architecture based on dynamically reconfigurable entanglement and the steps towards quantum error correction will be discussed. Finally, we will discuss opportunities for realization of useful, large-scale quantum processors.

A molecular bond between ions and Rydberg atoms

Tilman Pfau

5^{th} Institute of Physics and Center for Integrated Quantum Science and Technology, University of Stuttgart

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

Towards clocks at frequencies beyond the optical range

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Optical clocks are quickly becoming useful tools not only for technological applications, but also for New Physics searches. Thereby, the electronic wave function becomes an exquisite sensor for probing effects of hypothetical interactions, in analogy to the insights that hyperfine spectroscopy and the parity violation experiments in atomic systems provided early on. Extending the operation of atomic clocks beyond the optical requires narrow, forbidden transitions in electronic bound systems impervious to photoionization and subsequent Auger decay. Highly charged ions offer many options for this, since several isoelectronic sequences support such transitions, and their high ionization potentials preclude photoionization of the reference ion. The recent demonstration of an optical clock in the visible paves the way for exploring the extreme ultraviolet region. There, scaling laws strengthen the overlap of the nuclear and electronic wave functions, and magnify effects of QED and relativity, while reducing the polarizability of the bound system. These properties make highly charged ions very good candidates for frequency metrology at much higher photon energies than currently possible, with the promise of an enhanced sensitivity to physics beyond the Standard model. Our ongoing experiments combining an extreme ultraviolet frequency comb with cold highly charged ions will be discussed.

Exploring Large-Scale Entanglement in Quantum Simulation

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IQOQI, Austrian Academy of Sciences, Innsbruck, Austria

Entanglement is a distinguishing feature of quantum many-body systems, and uncovering the entanglement structure for large particle numbers in quantum simulation experiments is a fundamental challenge in quantum information science. In this talk we report experimental investigations of entanglement based on the Entanglement Hamiltonian, as an effective description of the reduced density operator for large subsystems. We prepare ground and excited states of a 1D XXZ Heisenberg chain on a 51-ion programmable quantum simulator and perform sample-efficient "learning" of the entanglement Hamiltonian for subsystems up to 20 lattice sites [1]. Our experiments provide compelling evidence for a local structure of the entanglement Hamiltonian. This observation marks the first instance of confirming the fundamental predictions of quantum field theory by Bisognano and Wichmann, adapted to lattice models that represent correlated quantum matter. The reduced state takes the form of a Gibbs ensemble, with a spatially-varying temperature profile as a signature of entanglement. Our results also show the transition from area to volume-law scaling of Von Neumann entanglement entropies from ground to excited states. As we venture towards achieving quantum advantage, we anticipate that our findings and methods have wide-ranging applicability to revealing and understanding entanglement in many-body problems with local interactions including higher spatial dimensions.

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PUBLIC LECTURES

The Alchemy of Vacuum

Thomas W. Ebbesen

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Over the past decade, the possibility of manipulating material and chemical properties by using hybrid light-matter states has stimulated considerable interest. Such hybrid light-matter states can be generated by strongly coupling the material to the spatially confined electromagnetic field of an optical resonator. Most importantly, this occurs even in the dark because the coupling involves the electromagnetic fluctuations of the resonator, the vacuum field. After introducing the fundamental concepts, examples of modified ground state properties of strongly coupled systems, such as magnetism, charge and energy transport, and chemical reactivity will be given to illustrate the broad potential of light-matter states.

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Nonenzymatic Metabolic Reactions and Life's Origins

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All dynamic self-organized systems found in nature are driven into existence when an energetic stress is relaxed under specific constraints. The self-organized chemistry that formed the basis for life should be no different. Due to the difficulty of making fundamental changes to a complex system that must operate continuously to support itself, drastic changes to the chemistry underlying the initial self-organized reaction network would be difficult, and thus basic features of "protometabolism" may still be found in metabolism [1]. To look for clues to the initial energetic stress (i.e., redox gradients, etc.) and constraints (i.e., natural catalysts, proton gradients, scale, temperature, etc.) that would have enabled self-organization, our team is experimentally evaluating the conditions under which nonenzymatic versions of highly conserved metabolic processes might occur [2-8]. We are also evaluating whether metabolites, especially coenzymes, can act as catalysts to reinforce reactions that were already happening within the network or to enable new ones – a necessary condition for the initial network to grow and to become more complex [9]. This talk will summarize our progress towards these goals.

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INVITED TALKS

Quantum diamond magnetometry at extreme pressures

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Diamond anvil cell (DAC) technology is commonly used to study materials under high pressure. The megabar regime above 100 GPa is an exciting frontier where matter exhibits specific quantum phases. For instance, superconductivity with record critical temperatures was observed in super-hydride materials where hydrogen combines to metallic or rare-earth elements in a novel stoichiometry allowed by the high pressure. This discovery opened a new window in the long standing search of room-temperature superconductivity. However at such extreme pressures, most conventional measurements methods fail or at least produce strongly biased results. I will describe the implementation of high-pressure magnetometry based on the optical detected magnetic resonance (ODMR) of nitrogen-vacancy (NV) centers that are atomic-like quantum systems [1]. Using a customized optical microscope, we use the NV spin dependent luminescence and the Zeeman dependence of the ODMR to map the magnetic field distribution at the diamond anvil tip. The Meissner effect results in a clear drop of the magnetic field in the vicinity of the sample where the NV sensors are located, leading to the unbiased detection of superconductivity. This measurement is compatible with synchrotron X-ray diffraction for dual structural characterization [2]. Moreover, imaging the Meissner effect with micrometer resolution reveals the existence of inhomogeneities in the sample whereas conventional probes give an averaged signal that discards any local information. I will discuss how this method can be implemented in the megabar regime by fabricating pillars on the anvil tip to create a quasi-hydrostatic stress environment for the NV centers [3]. This result enables the detection the Meissner effect of super-hydrides that is under stifling debate.

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Sub-symmetry protected topological states

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A hallmark of symmetry-protected topological phases are topological boundary states, which are immune to perturbations that respect the protecting symmetry. It is commonly believed that any perturbation that destroys such a topological phase simultaneously destroys the boundary states. However, by introducing and exploring a weaker sub-symmetry requirement on perturbations, we find that the nature of boundary state protection is in fact more complex. We demonstrate that the boundary states are protected by only the sub-symmetry, using Su-Schrieffer-Heeger and breathing Kagome lattice models, even though the overall topological invariant and the associated topological phase can be destroyed by sub-symmetry preserving perturbations [1]. By precisely controlling symmetry-breaking in photonic lattices, we experimentally demonstrate such sub-symmetry protection of topological states. Furthermore, we introduce a long-range hopping symmetry in breathing Kagome lattices, which resolves a debate on the higher-order topological nature of their corner states. Our results apply beyond photonics and could be used to explore the properties of symmetry-protected topological phases in the absence of full symmetry in different physical contexts.

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Engineering of many-body states in a driven-dissipative cavity QED system

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Exposing a many-body system to external drives and losses can fundamentally transform the nature of its phases, and opens perspectives for engineering new properties of matter. How such characteristics are related to the underlying microscopic processes is a central question for our understanding of materials. A versatile platform to address it are quantum gases coupled to the dynamic light fields inside optical resonators. This setting allows to create synthetic many-body systems with tunable, well-controlled dissipation channels, and at the same time to induce cavity-mediated long-range atom-atom interactions. If these are sufficiently strong, the system can undergo self-organization to a crystalline state. By engineering the involved light field modes, we study in real-time the dynamics of a phase transition between two such crystals. When the dissipation via cavity losses and the coherent timescales are comparable, we find a regime of limit cycle oscillations leading to a topological pumping of the atoms [Dreon et al., Nature, 608, 494 (2022)].

Precision molecular spectroscopy using optical frequency combs

Aleksandra Foltynowicz Matyba

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Fourier transform spectroscopy (FTS) based on optical frequency combs offers several advantages over conventional Fourier transform infrared (FTIR) spectroscopy. The high spectral brightness of the combs allows measuring molecular spectra with high signal-to-noise ratios in much shorter times, and their spatial and temporal coherence enables using multi-pass cells and cavities to increase the absorption sensitivity. Most importantly, the resolution of comb-based FTS is given by the linewidth of the comb modes rather than the optical path difference in the spectrometer, which implies that a resolution down to kHz level can be achieved, orders of magnitude better than in conventional FTIR spectrometers. We use comb-based FTS to measure high-resolution broadband spectra of molecules relevant to astrophysics and environmental monitoring. From these spectra we retrieve empirical line lists with sub-MHz accuracy of line positions. In particular, we measured and assigned fundamental bands of molecules such as N_2O, CH_4, H_2CO, CH_3I, and CH_2Br_2 in the mid-infrared range around 1250 cm^{-1} and 3000 cm^{-1}. To address hot-band transitions, we combined comb-based FTS with double-resonance spectroscopy and used it to measure and assign transitions in the $3\nu_3 \leftarrow \nu_3$ range of CH_4. Our data allows verification and significant improvement of theoretical models of the molecular spectra, which is important for applications ranging from astrophysical observations to atmospheric sensing

High accuracy predictions of properties of heavy atoms and molecules and evaluation of uncertainties

Anastasia Borschevsky

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Theory can provide important support at all the stages of spectroscopic experiments, from planning the measurements, through extracting the properties of interest from the data, and to the interpretation of the results and their comparison to theoretically predicted values. Such support is particularly valuable for the challenging precision measurements, aimed at testing the Standard Model. To be reliable and useful in experimental context, theoretical predictions should be based on high accuracy calculations. Such calculations must include both relativistic effects and electron correlation on the highest possible level.

Relativistic coupled cluster is considered one of the most powerful methods for accurate calculations of properties of heavy many-electron systems. This approach can be used to obtain ionization potentials, electron affinities, excitation energies, hyperfine structure parameters, and other atomic properties, and a variety of molecular properties. It has been shown to be extremely reliable and to have very strong predictive power. Recently, we have developed a scheme that allows us to use extensive computational investigations to assign uncertainties on the theoretical predictions [1], facilitating the use of these predictions in experimental context.

A brief introduction to the relativistic coupled cluster method will be provided and the new development for estimation of uncertainties will be presented. The talk will focus on recent successful applications of the coupled cluster approach to atomic and molecular properties, in particular in connection to recent and planned experiments [2-4].

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Challenging QED with atomic Hydrogen

Thomas Udem

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Precise determination of transition frequencies of simple atomic systems are required for a number of fundamental applications such as tests of quantum electrodynamics (QED), the determination of fundamental constants and nuclear charge radii. The sharpest transition in atomic hydrogen occurs between the metastable 2S state and the 1S ground state with a natural line width of only 1.3 Hz. Its transition frequency has been measured with almost 15 digits accuracy using an optical frequency comb and a cesium atomic clock as a reference [1]. A measurement of the Lamb shift in muonic hydrogen is in significant contradiction to the hydrogen data if QED calculations are assumed to be correct [2]. In order to shed light on this discrepancy the transition frequency of one of the broader lines in atomic hydrogen has to be measured with very good accuracy [3,4].

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Topology in orbital bosonic systems

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In this talk, we will discuss the physics of ultracold bosons loaded into the manifold of $l = 1$ orbital angular momentum (OAM) in lattices of ring potentials. In particular, for a diamond chain geometry, we will show that protected edge states and Aharanov-Bohm caging appear in the single particle case [1]. In the two-boson case, we will demonstrate that the interactions can be tuned to obtain a variety of two-body topological states and a special instance of Aharonov-Bohm cages [2]. In addition, we will present many-body Aharonov-Bohm caging by considering a few ultracold bosons loaded in a one-dimensional staggered lattice of rings. The spatial extent of the Aharonov-Bohm caging in this system can be tuned by modifying the periodicity [3]. In two dimensional lattices (2D), we will also demonstrate that bosons with OAM can be used to realize a 2D high order topological insulator [4]. Finally, we will also present the topological properties of interacting and non-interacting bosons loaded in a one dimensional lattice of rings with alternating distances forming a Su–Schrieffer–Heeger-like configuration. In this case, on-site interactions for the two-boson case lead to the appearance of multiple bound states and edge bound states [5].

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Fractal ground state, spectral properties, and quantum dynamics of one-dimensional Wigner crystals in periodic potentials

Giovanna Morigi

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We theoretically analyse the ground state of a one-dimensional Wigner crystal in the presence of a periodic potential. We show that the classical ground state is described by a long-range, anti-ferromagnetic Ising model and features a complete devil staircase as a function of the discommensuration between the two characteristic lengths: the lattice periodicity and the interparticle distance minimizing the Coulomb repulsion. Finite temperatures tend to smoothen the steps of the staircase: by means of our mapping we determine the size of the thermal crossover region. At zero temperature quantum effects at the commensurate- incommensurate phase transition are described by the long-range one-dimensional Thirring model. Our case study provides a detailed characterization of geometric frustration in long-range Coulomb systems that can be realised in trapped ion experiments.

Higgs excitation branch in Fermi superfluids

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Spin 1/2 Fermi gases are currently the subject of an interesting controversy over a fundamental question (made non-trivial by strong interactions): depending on the authors, these gases either do or do not have a collective Higgs excitation branch in their broken-pair continuum; e.g. the work of Laura Benfatto [1] belongs to the second category. In the first category, another disagreement exists: some suggest that the Higgs branch starts at 2 E_{gap} (where E_{gap} is the energy gap of fermionic excitations), e.g. Sandro Stringari [2], others claim that it starts at 2 Delta (where Delta is the order parameter of the U(1) symmetry breaking).

So far, this branch has not been observed in any system (not even superconductors). However, the recent experimental progress of Chris Vale's group (Swinburne, Australia) in a gas of fermionic cold atoms in the vicinity of a Feshbach resonance, which allows him to excite collective oscillations of the order parameter, makes the question a hot topic.

We have recently performed a very extensive theoretical study based on time-dependent BCS theory [3,4], now in the spotlight. We believe that we have clarified the problem and can reconcile the different schools of thought, as we have discovered two pitfalls to be avoided in the theoretical analysis that explain in particular the negative conclusion of Benfatto. We also propose an experimental procedure based on Bragg excitation [5], which Chris Vale or other groups in the world could implement quickly, and which would lead to a first observation of the Higgs branch and to an experimental resolution of the controversy.

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Attosecond spectroscopy of the electronic and vibrational dynamics in Furan

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We apply attosecond time-resolved carbon K-edge spectroscopy to investigate the ultrafast nonadiabatic relaxation pathways of furan after strong field excitation [1]. Disentangling the interplay of the various mechanisms, and how they lead to a specific flow of energy inside a molecular system, is extremely challenging since many of these effects occur on overlapping temporal scales. I will show, however, the extreme temporal resolution along with state and conformal sensitivity of AttoXAFS allows to disentangle the intricate interplay between of the electronic and nuclear wavepackets and extract a detailed picture of the rich dynamics that involves several parallel pathways, multiple CIs, electronic coherences and transiently populated dark states. Our method detects electronic-nuclear correlations, the dephasing of electronic coherence due to nuclear motion, and identifies the ring-opened isomer as the dominant product. These results demonstrate the efficacy of attosecond core level spectroscopy as a potent method to investigate the real-time dynamics of photochemical reaction pathways in complex molecular systems.

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Towards cold and controlled reactive collisions

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A primary goal in physical chemistry is to completely understand chemical reactions and the underlying dynamics on a molecular level. To achieve this, we investigate collisions and reactions between individual molecules and atoms in the gas-phase using the well-known crossed molecular beam approach. By using Zeeman deceleration in combination with Velocity Map Imaging (VMI) in our crossed-beam setup, we can study these molecular encounters in extremely high detail [1,2].

The decelerator produces beams of paramagnetic species with a well-defined and tunable velocity, narrow velocity spreads, and a high quantum-state purity, while VMI in combination with resonance-enhanced multi-photon ionization enables us to accurately probe the velocity vectors of the scattered products. This powerful combination of techniques enables scattering experiments with extraordinary resolution, revealing intricate features of molecular collisions, such as scattering resonances and diffraction oscillations.

Here, I will show how we use our approach to investigate reactive collisions between excited sulfur atoms and hydrogen or deuterium molecules. By investigating the collision-energy dependence of state-to-state differential cross sections, we aim to provide an extremely sensitive test for potential energy surfaces and scattering calculations used to describe the molecular reaction dynamics in this system.

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Quantum Technology, Quantum Simulations, and Precision Measurements with Ultracold Strontium

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In the last two decades, quantum simulators based on ultracold atoms in optical lattices have successfully emulated strongly correlated condensed matter systems. With the recent development of quantum gas microscopes, these quantum simulators can now control and observe ultracold atoms with single-site resolution. Within the same time period, atomic clocks have also begun to use optical lattices to trap alkaline earth metal atoms such as Sr, and they now interrogate the Sr optical qubit with precision and accuracy at the 10^{-18} level.

Here, we report on a new quantum simulator that combines quantum gas microscopy with optical lattice clock technology. We trap ultracold Sr atoms in large-mode-volume and highly state-dependent optical lattices to enable new kinds of quantum simulations that emulate strongly-coupled light-matter-interfaces in parameter regimes that are unattainable in real photonic systems. Furthermore, our Quantum Technologies open up new possibilities for neutral-atom quantum computers and optical lattice clocks.

As stepping stones towards these goals, we report on:

1. The most precise measurement of a tune-out wavelength to date which allows manipulating the Sr optical qubit with a state-specificity of more than 4 orders of magnitude.

2. A monolithic in-vacuum optical assembly with two crossed optical cavities. This device allows creating optical lattices with mode volumes $\sim 1\text{mm}^3$. Such large lattices allow scaling up the system size in quantum simulators, quantum computers, and optical lattice clocks by more than an order of magnitude, and they provide stable and robust atomic traps for transportable clocks and sensors.

3. The first high-resolution spectroscopy on the ultranarrow $1S_0$-$3P_2$ transition in neutral Sr. Using this transition, we isolate a large, two-dimensional layer of qubits underneath our quantum gas microscope.

Optical Traps for Ions & Ultracold Atoms

Tobias Schätz

Albert Ludwigs University Freiburg, Physikalisches Institut

Isolating ions and atoms from the environment is essential for experiments, especially if we aim to study quantum effects. For decades, this has been achieved by trapping ions with radiofrequency (rf) fields and neutral particles with optical fields. We are trapping ions by the interaction with light and electrostatic fields, in absence of any rf-fields. We take our results as starting point for studying how to combine the advantages of optical trapping and ions.

We aim to demonstrate the prospects of our approach in the context of interaction and reaction at ultra-low temperatures as a showcase. Following the seminal work in other groups in hybrid traps, we embed optically trapped ions into quantum gases to reach lowest temperatures, circumventing the currently inevitable excess kinetic energy in hybrid traps, where ions are kept but also driven by rf-fields.

We will also discuss our recent results on optically trapping $^{138}Ba^{+}$ and ^{6}Li atoms during our preparation stage, that is, still in our hybrid trap, where we observed Feshbach resonances and investigate their dependence on the collisional energy.

Quantum simulation of the dipolar XY model using Rydberg atom arrays

Thierry Lahaye

CNRS & Institut d'Optique, Palaiseau, France

In this talk, I will discuss quantum simulation of spin models using our Rydberg atom array platform. Using two different Rydberg levels nS and nP that are coupled by the resonant dipole-dipole interaction, we implement the dipolar XY Hamiltonian. I will first describe our quasi-adiabatic preparation of low-energy states of both the ferromagnetic and the antiferromagnetic XY model on a square array, with the observation of long-range order in the ferromagnetic case only [1]. I will then show that, in the same setting, a quantum quench starting from an initial state with all the spins pointing along the equator of the Bloch sphere givers rise to spin-squeezed states, with a squeezing parameter that increases with the atom number in the array [2], with potential applications for quantum metrology.

References

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Coherence of light from ensembles of many independent atoms

Lukáš Slodička[1], Artem Kovalenko[1], Lukáš Lachman[1], Dung Tran[1], Kratveer Singh[1], Petr Obšil[1], Radim Filip[1], Adam Lešundák[2], Tuan Pham[2], Ondřej Číp[2]

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Ensembles of atomic ions in Paul traps provide a unique testbed for a rich variety of quantum optics phenomena. The feasibility of precise and deterministic control of their external-motional and internal-electronic states has directly manifested in many photonic experiments requiring stable sub- wavelength localization and scalability to a large number of identical emitters. We present the observations of free-space optical emission from trapped ion crystals containing many independent emitters resulting in different paradig- matic regimes of statistics of light including extremely pure single photon emission or the largest discreet photonic nonclassical states [1]. We provide the experimental evidence of the single-modeness and of the phase coherence for light scattered from many ions [2, 3], which correspond to sufficient in- gredients for the efficient photonic generation of atomic entanglement or the directional control of optical emission from atoms [4]. We demonstrate en- hancement of the collection efficiency of light scattered from linear ion chains by tailoring their far-field interference pattern in a given solid angle. The achieved gains in photon detection probability for ions trapped in a single harmonic potential are comparable to the idealized case of equidistant emit- ters for realistic trapping parameters and laser cooling limits. The presented experiments constitute a unique toolbox for the generation and control of coherence and quantum statistics of light at the atomic level.

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From atoms and light to digital quantum computing

Shannon Whitlock

European Center for Quantum Sciences and aQCess - Atom Quantum Computing as a Service, Institut de Science et d'Ingénierie Supramoléculaires, University of Strasbourg and CNRS

Arrays of optically trapped atoms excited to Rydberg states have emerged as one of the most competitive scalable physical platforms for digital quantum simulation and quantum computing, approaching the point where reliable quantum computations with hundreds of qubits and realistically thousands of multiqubit gates with low error rates should be within reach for the first time. In Strasbourg we are building an open and public platform for digital quantum computing based on high quality qubits based on a dual species architecture. I will present our roadmap, focusing on the realization of a highly optimized universal gate set and advanced simulation tools for benchmarking and optimizing the performance of large scale quantum algorithms.

Observing Spin-Squeezed States under Spin-Exchange Collisions for a Second

Jakob Reichel

Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France

Spin squeezing is a fascinating manifestation of many-particle entanglement as well as one of the most promising quantum technologies. Groundbreaking experiments have demonstrated methods for creating spin-squeezed states and proof-of-principle clocks and magnetometers have been realized. However, previous squeezing experiments with alkali atoms have been limited to time scales of a few milliseconds, while interrogation times in real clocks and sensors are typically ten to hundred times longer. At these longer timescales, fundamental effects are expected to arise from atomic interactions, but remained hidden in earlier experiments due to technical noise. In a recent experiment in collaboration with SYRTE (Observatoire de Paris) using the platform of a trapped-atom clock on a chip, we have observed the time evolution of spin-squeezed hyperfine clock states on previously inaccessible time scales up to 1 s. The spin degree of freedom remained squeezed after 0.6 s, which is consistent with the limit imposed by particle loss and is compatible with typical Ramsey times in state-of-the-art microwave clocks. The results revealed a surprising spin-exchange interaction effect that amplifies the cavity-based spin measurement via a correlation between spin and external degrees of freedom. I will discuss perspectives for squeezing-enhanced atomic clocks in metrologically relevant regimes and highlight the importance of spin interactions in real-life applications of spin squeezing.

Ultracold atoms in ring traps: from fundamentals to atomtronics applications

Anna Minguzzi

LPMMC - Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS and Université Grenoble Alpes

Atomtronics is an emerging field that aims to manipulate ultracold atom moving in matter-wave circuits for fundamental studies in both quantum science and technological applications. I will present the principles of persistent currents for atoms subjected to artificial gauge fields. For the case of a tight transverse confinement, where the system is effectively one-dimensional, I will detail the theoretical models we use to account for the effects of interactions, from weak to strong. I will then present our results on the persistent currents for both bosons and multi-component Fermi gases, as well as the readout protocols envisaged. Finally, I will discuss possible applications to quantum technologies.

CONTRIBUTED TALKS

A Cold gases and quantum fluids

A.1 Microscopically-controlled arrays of alkaline-earth atoms

Nelson Darkwah Oppong[1]

[1]JILA, University of Colorado and National Institute of Standards and Technology
Department of Physics, University of Colorado

I will describe recent work in which we use microscopically-controlled arrays of alkaline-earth atoms for experiments in quantum information science. While their increased complexity leads to challenges, alkaline-earth atoms offer new scientific opportunities by virtue of their rich internal degrees of freedom. I will report on how these degrees-of-freedom can cooperate with optical-tweezer-based single-particle control to impact areas ranging from quantum information processing, to quantum metrology, and quantum simulation.

A.2 Cavity-QED Quantum Simulator of Random Spin Models

Francesca Orsi[1], N. Sauerwein, P. Uhrich, S. Bandyopadhyay, F. Mattiotti, T. Cantat-Moltrecht, G. Pupillo, P. Hauke, J.P. Brantut, J. Faltinath, R. Bhatt, G. S. Bolognini

[1]Ecole Polytechnique Fédérale de Lausanne

Cavity QED systems have recently proved their value and flexibility in the field of quantum simulation, in particular for the long-range interactions that the cavity field mediates between the atoms.

In this context, we have realised a random spin model with atoms in a cavity where we introduce controlled disorder in the atomic transition frequencies with a light-shift of the excited state. We study the competition between the collective many-body physics and the disorder in two regimes: in the near-resonant regime, N spins with random energies are coupled to a bosonic mode. In the dispersive regime, one can adiabatically eliminate the cavity to obtain long-range spin-exchange interactions. The effective Hamiltonian can be rewritten in terms of N spins precessing around an external magnetic field with random inhomogeneities. In this regime we observe the ferromagnetic gap of our system closing as a function of the disorder strength.

Last, I will discuss how we want to combine the use of a microscope and a modulation of our light-shifting beam to locally control the atom-cavity coupling and tailor the long-range interactions.

A.3 Dark state transport in a strongly interacting fermi gas

Mohsen Talebi[1], Philipp Fabritius[1], Jeffrey Mohan[1], Simon Wili[1], Meng-Zi Huang[1], Tilman Esslinger[1]

[1]Department of Physics, ETH Zürich

We investigate experimentally the influence of a spin-selective electromagnetically induced transparency (EIT) on the transport of a fermionic superfluid. We prepare a unitary Fermi gas of lithium-6 atoms in a two-reservoir geometry connected via a quantum point contact (QPC). In this setting, the EIT scheme is realized via the introduction of a local Lambda system in the QPC region that connects one of the interacting states to an auxiliary ground state. We first study the case of both weak (probe) and strong (control) beams of the EIT scheme on resonance. In the absence of the control beam, the probe beam works as a spin-dependent particle loss mechanism slowing down the non-Ohmic superfluid transport between the two reservoirs [1]. Here, we observe the revival of this fast current as the power of the control beam is increased, which is attributed to the dark state transport. We extend this study to the case of an off-resonant control beam. In this situation, we observe an asymmetry in the transport with respect to the control detuning: for the blue detuning, the transport is faster than for the red detuning. We show that this is due to the conservative potential of the Lambda system close to the resonance. This work paves the way for further research on the use of dark state schemes in strongly correlated fermionic systems.

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A.4 Self-Pinning Transition of impurities in a Bose-Einstein Condensate

Thomas Busch[1], T. Keller[1], T. Fogarty[1]

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We show that a Tonks-Girardeau (TG) gas that is immersed in a Bose-Einstein condensate can undergo a transition to a crystal-like Mott state with regular spacing between the atoms without any externally imposed lattice potential. We characterise this phase transition as a function of the interspecies interaction and temperature of the TG gas, and show how it can be measured via accessible observables in cold atom experiments. We also develop an effective model that accurately describes the system in the pinned insulator state and which allows us to derive the critical temperature of the transition.

We will also show how extending the above idea to multicomponent TG gases can lead to the spontaneous emergence of more complex crystal structures with antiferromagnetic order, and how finite interactions in the immersed component lead to additional superfluid phases.

A.5 Melting of a vortex lattice in a fast rotating Bose gas

R. Sharma, D. Rey, T. Badr, A. Perrin, L. Longchambon, R. Dubessy, Hélène Perrin[1]

[1]CNRS and Université Sorbonne Paris Nord

Quantum gases offer great flexibility to study general problems of quantum physics through their extended manipulation and imaging tools. In particular, they offer a natural playground for the study of superfluid dynamics, made possible by the existence of interactions between atoms. Superfluids are characterized by an ensemble of specific properties, including the absence of viscosity, existence of a critical velocity for excitation, and the irrotational character of a superfluid flow. In the presence of applied rotation, trapped superfluid develop a number of quantum vortices that arrange in a regular triangular lattice at very low temperature, the Abrikosov lattice. As temperature increases, however, the Abrikosov lattice is expected to be gradually destroyed, by displacement of the vortex centers and eventually strong phase fluctuations. In our experiment, we rotate a rubidium quantum gas in a very smooth oblate potential arising from a combination of magnetic and radiofrequency fields. We image the vortex lattice after a time-of-flight expansion and characterize the order of the vortex lattice by measuring the correlations between vortex positions, as a function of the temperature and the rotation frequency. We observe the melting of the vortex lattice at large rotation frequency and finite temperature. We compare our findings to the theoretical predictions of Gifford and Baym [1].

References

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A.6 Polarons and their mediated interactions in Fermi-Bose and Fermi-Fermi mixtures of Li and K

Cosetta Baroni[1]

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We present our recent radio-frequency spectroscopy experiments on impurities in strongly interacting imbalanced Fermi-Bose and Fermi-Fermi mixtures. Our ultracold system consists of a Fermi sea of 6Li, in which either bosonic 41K or fermionic 40K impurities are embedded. We first investigate the Fermi-Bose mixture in the two cases of thermal impurities and of impurities forming a partial Bose-Einstein condensate. In the thermal case, and for the thermal part of a partially condensed impurity cloud, we find good agreement between the recorded energy spectrum and the theory for isolated polarons. Moreover, we observe hints on mediated interactions between polarons for increasing impurity concentration. In the case of condensed impurities, we observe the emergence of an additional branch in the impurity energy spectrum, which can be explained by the presence of Bose polarons created by fermionic Li impurities in the K condensate. In our system we thus observe the coexistence of Fermi and Bose polarons. We then investigate more closely the effect of increasing the impurity concentration on the impurity energy spectrum and observe, for the first time, mediated interactions between polarons. In order to understand how this effect is affected by different quantum statistics, we employ either bosonic or fermionic thermal impurities. In the single impurity limit, as expected, we do not observe any difference in the respective energy spectra. For higher impurity concentration we observe the experimentally challenging weak effect of the mediated polaron-polaron interaction. In particular, we unambiguously detect the influence of the quantum statistics, which manifests itself as a sign inversion in the mediated polaron-polaron interaction.

A.7 An interaction-driven Otto heat engine using a harmonically trapped Lieb-Liniger gas

Karen Kherunstsayn[1], R. S. Watson[1]

[1]University of Queensland

Quantum many-particle heat engines have been the subject of growing interest in recent years in the emerging field of quantum thermodynamics. Such engines are known to be capable of outperforming an ensemble of single-particle engines operating with the same resources. This implies a quantum advantage over classical heat engines, which has the potential to be utilised in future quantum technologies. Many-particle heat engines can be experimentally realised using ensembles of ultra-cold atomic gases, which offer a versatile platform for addressing fundamental questions of quantum thermodynamics in a laboratory setting. Here, we propose a quantum many-particle Otto engine using a harmonically trapped one-dimensional Bose gas as the working fluid. The advantage of using the 1D Bose gas is that the underlying theoretical model—the Lieb-Liniger model—is exactly soluble in the uniform limit. This offers unique opportunities for gaining theoretical insights into the performance of such an engine as a tractable quantum many-body problem. In addition, the 1D Bose gas has a rich equilibrium phase diagram, which spans many nontrivial regimes, from a weakly interacting quasi-condensate through to the strongly interacting Tonks-Girardeau regime of fermionisation. As such, the 1D Bose gas offers an experimental platform for realising quantum many-body heat engines in novel settings. In this work, we take advantage of the many theoretical tools and exact results, available for the Lieb-Liniger model, and investigate the performance an interaction-driven Otto heat engine in different regimes, in the interaction strength, temperature, and total atom number parameter space. Focusing on the total work output and efficiency of the engine, we show how these fundamental quantities can be simply expressed and calculated in terms of the pair correlation function and other equilibrium observables of the Lieb-Liniger model.

A.8 Spin-squeezed states with ultracold fermions

Mažena Mackoit-Sinkevičienė[1], Tanausú Hernández Yanes[2], Marcin Płodzień[3], Giedrius Žlabys[4], Domantas Burba[1], Gediminas Juzeliūnas[1], Emilia Witkowska[2]

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Generation, storage, and utilisation of correlated many-body quantum states are crucial objectives of future quantum technologies and metrology. Such states can be generated by the spin-squeezing protocols. In this work, we consider the dynamical generation of spin squeezing in a lattice system composed of ultra-cold fermionic atoms in the Mott phase at half-filling. To induce the generation of squeezing, we add the position-dependent laser coupling between the internal degrees of freedom of atoms. We study the Ramsey-type spectroscopy scheme in which the atom-light coupling is turned on during the interrogation time. By choosing an appropriate propagation direction of the laser beam inducing the spin-orbit coupling and acting on a fermionic lattice with a sequence of such laser pulses we expect to realise efficient spin-squeezing. We show analytically, using the perturbation theory, how the Fermi-Hubbard model with the atom-light coupling effectively simulates the one-axis twisting model with the tunable axis of squeezing. This paves the way for the simulation of the famous two-axis counter-twisting model when two laser couplings are used during interrogation time. The presented method might deliver gains in real applications like optical clocks.

A.9 Fractional angular momentum quantization in Atomtronic circuits

Juan Polo[1]

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Bosonic systems guided in a ring-shaped atomtronic circuit present quantized values of the winding number. In this talk, I will show cases for which fractional values of winding number quantization occurs. First I will consider attracting bosonic systems. Then, I will discuss fermionic systems with N components that present SU(N) symmetry. For repulsive interactions a specific emerging phenomenon of attraction from repulsion appears, providing a quantization with similar properties to the attracting boson case. For attractive interactions, the quantization is determined by the number of components N.

B Quantum optics, quantum information and quantum simulation

B.1 Strong dual dressing of a Rb qubit

Andrea Fioretti[1], Alessandro Fregosi, Carmela Marinelli, Carlo Gabbanini, Giuseppe Bevilacqua, Valerio Biancalana, Ennio Arimondo

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Periodically driven quantum systems represent an interesting playground to realize different types of effective Hamiltonians. In the present analysis, the addition of a secondary radiofrequency field strongly dressing atomic spins enhances and enriches the quantum dynamics of a qubit in an external magnetic field. The dual-dressing configuration introduces an extra handle for the qubit Floquet engineering, useful for quantum control applications. Tuning amplitude, harmonic content, spatial orientation and phase relation are the control parameters. This secondary field allows for a more complete tuning of the atomic response and produces qubit features not accessible with a single dressing field. The explored Floquet engineering regime extends over dressing field amplitudes larger than the dressing frequencies. The theoretical analysis is experimentally validated in a cold-atom Rb magnetometer. Here a static magnetic field around 30 μT, two radiofrequency magnetic fields, frequencies in the 20-150 kHz range and amplitudes in the 0.3 mT range, are applied along orthogonal directions to the free-falling cold atoms. The atomic magnetization, evolving on the Bloch sphere determined by an effective Larmor frequency and by a micromotion at the dressing frequency and harmonics, is probed through the Faraday rotation. Dual dressing features are explored by measuring the frequency shift, phase and amplitude of the resonance. The Fast Fourier Transform and the recording of the complete temporal qubit dynamics allow a global investigation of the Floquet engineering dynamics.

B.2 Tailoring photon statistics with an atom-based two-photon interferometer

Maximilian Schemmer[1,2], Martin Cordier[2], Philipp Schneeweiss[2], Jürgen Volz[2], Arno Rauschenbeutel[2]

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Controlling the photon statistics of light is paramount for quantum science and technology. Recently, we demonstrated that transmitting resonant laser light past an ensemble of two-level emitters can result in a stream of single photons or excess photon pairs. This transformation is due to quantum interference between the transmitted and incoherently scattered two-photon component. Here, we use the dispersion of the atomic medium to actively control the relative quantum phase between these two components, thereby realizing a tunable two-photon interferometer. The interferometer setup consists of laser-cooled caesium atoms weakly coupled to an optical nanofiber. When probing the ensemble of effective two-level emitters with resonant light (D2-line) in transmission, two-photon scattering at the atoms generates incoherent photon-pairs that interfere with the two-photon components of the incoming light. Here we show how the relative amplitude and phase of these incoherent photon pairs can be tuned by controlling the number of atoms and the detuning of the laser light. The observed interference fringes in the normalized photon coincidence rate, vary from antibunching to bunching. Beyond the fundamental insight that the quantum phase between incoherent and coherent light can be tuned and dictates the photon statistics, our results lend themselves to the development of novel quantum light sources.

Ref.: Cordier et al., arXiv.2212.0959

B.3 A hybrid quantum system of ultracold polar molecules and Rydberg atoms

Daniel Ruttley[1], Alexander Guttridge[1], Stefan Spence[1], Archie C. Baldock[1], Robert C. Bird[2], C. Ruth Le Sueur[2], Jeremy M. Hutson[2], Rosario González-Férez[3], H. R. Sadeghpour[4], C. S. Adams[1], Simon L. Cornish[1]

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We envision a hybrid quantum system of individually trapped polar molecules interfaced with Rydberg atoms. Quantum information is encoded in the molecules' long-lived rotational states, whilst strong long-ranged interactions between a polar molecule and Rydberg atom allow for fast multi-qubit quantum gates. Here we report recent experimental progress towards this goal where we have observed the blockade of the excitation of a Rb atom to the 52s Rydberg state due to the charge-dipole interaction with a ground state RbCs molecule [1]. We produce single RbCs molecules in optical tweezers which allows for single-site control and imaging. Individual Rb and Cs atoms are first trapped and cooled in separate tweezers. The tweezers are then merged to prepare Rb-Cs atom pairs. Weakly bound molecules are formed by associating these atom pairs [2] and are subsequently transferred to their rovibrational ground state using STIRAP. Alongside the molecules, excess Rb atoms are prepared and excited to Rydberg states. The atom and molecule are held in species-specific tweezers which allows them to be brought to a separation of 310(40) nm without significant collisional loss. The polar molecule perturbs the Rydberg state energy to be off-resonant with the two-photon excitation. This blockades the Rydberg excitation. The observed excitation dynamics are in good agreement with simulations using calculated interaction potentials. We present an outlook to future work including our plans to use this hybrid system to photoassociate giant polyatomic Rydberg molecules [3,4] and test schemes for non-demolition readout of the quantum state of the molecule [5].

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B.4 Tunable long-distance mediated interactions in quantum simulators with cold atoms

Javier Arguello-Luengo[1]

[1]ICFO - The Institute of Photonic Sciences

Engineering long-range interactions in cold-atom quantum simulators can lead to exotic quantum many-body behaviour, becoming and enabling tool in the simulation of relevant problems in condensed matter or quantum chemistry [1]. In addition to current efforts with bosonic species [2,3], fermionic atoms in ultracold atomic mixtures can also act as mediators. This gives rise to long-range Ruderman-Kittel-Kasuya-Yosida–type interactions characterized by the dimensionality and density of the fermionic gas, as it was revealed in recent experiments [4,5].

In this work, we propose several tuning knobs, accessible in current experimental platforms, that allow one to further control the range and shape of the mediated interactions, extending the existing quantum simulation toolbox [6]. In particular, we include an additional optical lattice for the fermionic mediator, as well as anisotropic traps to change its dimensionality in a continuous manner. This allows us to interpolate between power-law and exponential decays, introducing an effective cutoff for the interaction range, as well as to tune the relative interaction strengths at different distances. Finally, we show how our approach allows one to investigate frustrated regimes that were not previously accessible, where symmetry-protected topological phases as well as chiral spin liquids emerge.

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B.5 Interfacing Rydberg atoms with superconducting microwave circuits - state control and tunability

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Rydberg atoms are well suited to interfacing with superconducting microwave circuits for applications in hybrid quantum information processing [1-4]. This is because of their large electric dipole transition moments at microwave frequencies, and long coherence times. Recently, helium Rydberg atoms were coherently coupled to the 19.556 GHz mode of a quarter-wavelength niobium nitride coplanar waveguide resonator [4-6]. This resonator field drove the two photon 55s-56s transition between triplet Rydberg states. As will be presented in this talk, to extend this work, with the goal of accessing the single-photon strong-coupling regime of this hybrid cavity QED system, a refined experimental scheme with addition of two nonresonant microwave fields has been developed. These fields (1) null the polarizability [7-9] of the 55s-56s transition so that the atoms can be located closer to the surface of the cryogenically cooled superconducting chip where the microwave field is stronger without detrimental effects from stray electric fields, and (2) allow the implementation of two-color microwave transitions for the absorption of single single photons from resonator. The resulting engineered helium Rydberg atom qubit is particularly well suited to applications in quantum technologies, including, e.g., microwave to optical photon conversion.

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B.6 Trapped ions in an ultracold gas: buffer gas cooling and chemical reactions

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Hybrid ion-atom systems combine the benefits of a single, well-controlled ion with those of a many-body quantum gas, offering prospects for quantum simulation, ultracold chemistry, and charged impurity physics. In this talk I will present recent experiments, where we observed collisions between Li_2 dimers and a single Yb+ ion, leading to the formation of a LiYb+ molecular ion [1]. Our results show a new method for molecular ion formation and for probing an atom cloud for small quantities of dimers. Furthermore, I will present numerical simulations for atom-ion collisions in our system and in other ion traps. We find that ion trap parameter optimization in a radiofrequency trap will allow buffer gas cooling further into the quantum regime [2], to atom-ion collision energies twice as cold as previous experiments [3]. Meanwhile, investigations into the formation of temporary, trap-assisted complexes gives us insight into the rate of three-body collisions, both in radiofrequency traps and in time-independent harmonic traps [4].

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B.7 Enhancement in multiphoton absorption measurements with squeezed light

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Multiphoton absorption processes are nonlinear processes in which a sample is excited by absorbing several photons simultaneously. These processes can surpass the single-photon diffraction limit, resulting in enhanced spatial resolution, and pushing the resolution of optical microscopy to molecular scales. The applications of multiphoton absorption processes include 3D microfabrication, spectroscopy, and microscopy [1]. These advantages offered by mPA are challenged by their weakness of nonlinear light-matter interactions (very small multiphoton absorption cross sections). The proposed method to overcome this issue is to use strong ultrafast lasers.

Here, we propose another method based on the utilization of a nonclassical light source (squeezed light) inside a platform known as a nonlinear interferometer. The main difference in nonlinear interferometers compared to their Mach–Zehnder counterparts is the replacement of the beam splitters with nonlinear crystals such as optical parametric amplifiers (OPA) [2]. We show that by optimization of the nonlinear interferometer, it is possible to improve the precision of measuring the cross-section of multiphoton absorption processes. Furthermore, we show that in the presence of realistic competing losses, optimized quantum states always created inside the interferometer outperform classical measurement strategies [3].

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B.8 Detecting of high-dimensional entanglement with quantum gas microscopes

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Quantum entanglement is a crucial concept underlying many intriguing phenomena in condensed matter systems such as topological phases or many-body localization. Recently, instead of considering mere quantifiers of entanglement like entanglement entropy, the study of entanglement structure in terms of the entanglement spectrum has shifted into the focus leading to new insights into fractional quantum Hall states and topological insulators, among others. What remains a challenge is the experimental detection of such fine-grained properties of quantum systems. The development of protocols for detecting features of the entanglement spectrum in cold atom systems, which are one of the leading quantum simulation platforms, is thus highly desirable and will open up new avenues for experimentally exploring quantum many-body physics. I will present a method to bound the width of the entanglement spectrum, or entanglement dimension, of cold atoms in lattice geometries, requiring only measurements in two experimentally accessible bases and utilizing ballistic time-of-flight expansion. Specifically, building on previous proposals for entanglement certification for photon pairs, we consider entanglement between atoms of different atomic species and derive general measurable entanglement dimension witnesses, also for multispecies configurations showing multipartite high-dimensional entanglement. Through numerical simulations of a different Hubbard system we show that our method is robust against typical experimental noise effects and the required measurement statistics is manageable.

C Fundamental physics

C.1 Steering edge currents through a Floquet topological insulator

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Periodic driving may cause topologically protected, chiral transport along edges of a 2D lattice that, without driving, would be topologically trivial. We study what happens if one adds a different on-site potential along the diagonal of such a 2D grid. In addition to the usual bulk and edge states, the system then also exhibits doublon states, analogous to two interacting particles in one dimension. A particle initially located at an edge propagates along the system's boundary. Its wave function splits when it hits the diagonal and continues propagating simultaneously along the edge and the diagonal. The strength of the diagonal potential determines the ratio between both parts. We show that for specific values of the diagonal potential, hopping onto the diagonal is prohibited so that the system effectively separates into two triangular lattices. For other values of the diagonal potential, we find a temporal delay between the two contributions traveling around and through the system. This behavior could enable the steering of topologically protected transport of light along the edges and through the bulk of laser-inscribed photonic waveguide arrays.

Ref.:arXiv:2204.08873, accepted for publication in Physical Review Research

C.2 AION: A UK collaboration searching for gravitational waves and dark matter with a large-baseline differential atom interferometer

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The Atom Interferometer Observatory and Network (AION) is a UK collaboration using differential atom interferometry to detect gravitational waves and search for dark matter [1]. The project plans a hundred-metre vertical detector soon, with plans in place to proceed to a kilometre-scale detector and, ultimately, a satellite pair. The detector will have sensitivity to gravitational waves in the mid-band frequency range, a range unavailable to current and planned alternative detectors and that permits observation of black hole mergers at smaller masses and for longer periods than currently possible, enabling multi-messenger astronomy and opening a new window to our universe. In this talk, I will outline the principles behind our detector's sensitivity to fundamental physics, both scalar dark matter and gravitational waves. Our project relies on single-photon interferometry for laser noise rejection which motivates our choice of the clock isotope strontium-87. To reach the performance levels necessary for our fundamental physics goals, the AION programme involves seven groups in the UK at Imperial College London, Kings College London, Birmingham, Oxford, Cambridge, Liverpool and the Rutherford Appleton Laboratory. I will overview the technologies we are developing, including large momentum transfer interferometry [2], high atom-number sources and optically transported ultracold atoms, and our progress towards a ten-metre prototype detector based in Oxford. Finally, I will go into more detail on the Imperial contribution to AION – the generation of entangled, squeezed states to measure atom phase below the standard quantum limit (SQL). We use a cavity non-demolition measurement to create entanglement between an ensemble of atoms trapped by an optical lattice with uniform atom-cavity coupling and high cooperativity [3]. Squeezing is achieved through interrogation of the vacuum Rabi splitting – we anticipate an improvement over the SQL to the interferometer readout of up to 14.6 dB.

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C.3 Searching for ultralight dark matter with $^{171}Yb^{+}$ clocks

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To realize a high-accuracy optical clock, the 2S1/2-2F7/2 electric octupole (E3) transition in $^{171}Yb^{+}$ is well-suited. The same ion also features an electric quadrupole (E2) transition that can be used as an ancillary transition to study external fields with high precision. Because the two transitions have a large differential sensitivity to the fine structure constant α, tight limits on possible variations can be obtained by comparing their frequencies at various positions in spacetime [1,2]. These limits can then be used to constrain models predicting such variations. In particular, the couplings of so-called ultralight bosonic dark matter to standard model particles would lead to coherent oscillations of constants, with an oscillation frequency corresponding to the Compton frequency of the dark matter mass [3]. We conduct a broadband dark-matter search by comparing the frequency of the E3 transition to that of the E2 transition, and to that of the 1S0 $\leftrightarrow$ 3P0 transition in ^{87}Sr. We find no indication for significant oscillations in our experimental data, and improve existing bounds on the scalar coupling of UBDM to photons for dark-matter masses of about 10^{-24} to 10^{-17} eV/c^2 [2]. As recently shown, couplings to quarks and gluons can also be investigated with optical frequency ratio measurements by considering the effect an oscillating nuclear charge radius would have on electronic transitions [4]. Alternatively, an optical frequency can be compared to a microwave clock based on a hyperfine transition, such as a Cs fountain clock.

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C.4 Tunneling measured in a very slow ion-molecule reaction

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Quantum tunneling reactions play an important role in chemistry when classical pathways are energetically forbidden [1]. In general, such tunneling reactions are challenging to calculate theoretically, given the high dimensionality of the quantum dynamics, and also very difficult to identify experimentally. Binary collisions of atomic with molecular hydrogen belong to the most fundamental molecular systems and are simple enough to be theoretically investigated using first-principle calculations. Additionally, hydrogen is the most abundant element in the universe, and collisions of hydrogen and its charged forms are important in the chemistry and evolution of the interstellar medium. The rate of the tunneling reaction $H_2 + D^- \rightarrow HD + H^-$ has been calculated [2] but has until now lacked verification. Here we present high-sensitivity measurements of the reaction rate carried out in a cryogenic 22-pole ion trap. A deviation of the reaction rate from linear scaling, which is observed at high H2 densities, can be traced back to previously unobserved heating dynamics in radiofrequency ion traps. Our measured value agrees with quantum tunneling calculations, serving as a benchmark for molecular theory and advancing the understanding of fundamental collision processes [3].

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C.5 The Frustration of Being Odd

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We consider the effects of so-called Frustrated Boundary Conditions (FBC) on quantum spin chains, namely periodic BC with an odd number of sites. In absence of external fields, FBC allow for the direct determination of correlation functions that signal a spontaneous symmetry breaking, such as the spontaneous magnetization. When paired with anti-ferromagnetic interactions, FBC introduce geometrical frustration into the system and the ground state develops properties which differ from those present with other boundary conditions, such as the disappearance of the usual order, possibly replaced by different ones. We argue that FBC introduce a fractionalized excitation that contributes to long-range order in the system, similar to that enjoyed by SPT phases. Our results prove that even the weakest form of geometrical frustration can deeply affect a system's properties and pave a way for a bottom-up approach to better understand the effects of frustration and their exploitations also for technological purposes.

Ref.: J. Phys. Commun. 3, 081001 (2019); New J. Phys. 22 083024 (2020); Comm. Phys. 3, 220 (2020); J. Phys. A 54 025201 (2020); Phys. Rev. B 103, 014429 (2021); Sci Rep 11, 6508 (2021); Phys. Rev. B 105, 064408 (2022); Phys. Rev. B 105, 184424 (2022); SciPost Phys. 12, 075 (2022)

D Quantum technology applications of AMO Physics

D.1 Interacting Laser-Trapped Circular Rydberg Atoms

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Rydberg atoms, i.e., atoms with a high principal quantum number n, are particularly well suited to the quantum simulation of interacting spins, thanks to their strong dipole-dipole interactions, even at a few microns. While regular arrays of hundreds of Rydberg atoms have been used in several experiments, the effective simulation time is ultimately limited to a few μs by the $\sim 100\mu$s lifetime of the employed laser-accessible Rydberg levels.

Circular Rydberg atoms, with maximal orbital momentum, have a natural lifetime that reaches several 10ms. Quantum simulation with circular Rydberg atoms could then be run over unprecedented timescales [1], making it possible to study slow spin dynamics, that escape both numerical and current quantum simulations. To benefit from these long lifetimes, however, makes laser-trapping of circular Rydberg atoms mandatory [2].

Here, I will present our latest experimental results regarding the laser-trapping of individual circular Rydberg atoms in a regular array of optical tweezers and the observation of their dipole-dipole interactions.

We use so-called bottle optical beams as hollow optical tweezers to ponderomotively trap individual circular Rydberg atoms with n=52. We demonstrate their laser-trapping over several milliseconds, limited by their 130μs lifetime in our room-temperature setup, and observe their oscillations in the traps. To this end, we have developed an optical detection method of circular Rydberg levels, that is both level and spatial selective [3]. We also use this method to characterize the dipole-dipole interaction between two nearby laser-trapped circular Rydberg atoms [4].

Our results open a new route for quantum technologies with Rydberg atoms, allowing one to exploit the unique properties of the circular levels.

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D.2 Multi-parameter quantum sensing and magnetic communications with a hybrid dc/rf optically-pumped magnetometer

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Optically-pumped magnetometers (OPMs) [1] are paradigmatic quantum sensors that provide insight into quantum sensitivity limits [2]. Quantum enhancement of OPM sensitivity to single dc [3-5] and rf [6-7] field components, and to a single rf gradient component [8] have been demonstrated. Multi-parameter quantum sensing [9] aims to extend quantum enhancement to simultaneous measurement of multiple physical parameters, for example using spin uncertainty relations to escape trade-offs present in other quantum systems [10-11]. Here we report an OPM capable of simultaneously measuring dc and rf fields with quantum-limited sub-pT/$\sqrt{\text{Hz}}$ sensitivity, making it a practical test-bed for quantum multi-parameter estimation (MPE). We use this OPM to demonstrate MPE-enabled spread spectrum magnetic communication, with possible application in ultra-compact radio receivers [12] for communication underwater [13], underground [14], and in planetary exploration.

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E Applications to astrophysics, plasma physics, biophysics, clusters, ...

E.1 Upcoming atomic physics studies of ion-ion collisions

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The fundamental electronic processes occurring in ion-ion collisions play a major role in energy transfer in laboratory and astrophysical plasmas and in applications where ion-matter interactions take place. The so-called intermediate velocity regime where the ion stopping power is maximum is complex to study since there the electronic processes have comparable cross sections. This collision regime reached when the relative velocity between target and projectile is comparable to the average velocity of active electrons in the initial state has been little investigated leading to a lack of experimental data and theoretical predictions.

It is in this context that the FISIC (Fast Ion Slow Ion Collisions) project has been launched. Experimentally, a mobile platform that delivers keV/u ion beams is developed to perform ion-ion collisions, both at the SIMPA facility in Paris and at the CRYRING@ESR storage ring in Germany [1]. Theoretically, the project concerns the coupled channel description of electronic processes within the framework of the semi-classical approximation: the relative motion between target and projectile ions is described classically while the electron dynamic is treated by solving non perturbatively the time dependent Schrödinger equation, with a spectral method [2]. The related code allows the modelling of systems and processes with up to 4 active electrons.

As a first step towards the exploration of the intermediate velocity regime for various highly charged ion-ion systems, experimental and theoretical works are being conducted for light ions in the keV/u regime. We report here the theoretical results obtained for several collision systems involving carbon, hydrogen, nitrogen and helium ions. Cross sections for electron capture as well as excitation and ionization will be presented and compared to independent data when available in the literature.

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F Frequency and time domain spectroscopy and metrology

F.1 Precision Spectroscopy of highly charged ions with sub-Hz uncertainty

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Highly charged ions (HCI) are promising candidates for a next generation of optical clocks with application for frequency metrology and tests of fundamental physics [1]. Typically, the megakelvin environment in which HCI are produced does not allow for high precision spectroscopy. In our experiment, HCI are extracted from an electron beam ion trap (EBIT) and transferred to a linear Paul trap. There, single HCI are confined together with laser cooled beryllium ions for sympathetic cooling and quantum logic readout [2]. The systematic uncertainties of the apparatus were fully evaluated to the low 10^{-17} range and an optical clock based on Ar^{13+} was demonstrated. By comparing it to an established optical clock at PTB the absolute frequency and isotope shift was measured with sub-Hz uncertainty [3]. The developed techniques are readily applied to other systems. Recently, we measured the isotope shift of a narrow M1 transition in stable even isotopes of Ca^{14+} to conduct a King plot analysis. This can be used for the search of a hypothetical fifth force coupling neutrons and electrons [4] and to probe fundamental physics in combination with existing data of the clock transition in Ca^{+} [5]. Here we present results of the Ar^{13+} clock campaign, the recent isotope shift measurements in Ca^{14+} and provide an outlook to future optical clock candidates and the search strategy for their clock transitions.

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F.2 Frequency-comb-driven atom interferometry

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Light-pulse atom interferometry, where light pulses are used as atom beam splitters, has led to extremely sensitive and accurate quantum sensors that offer many applications in fundamental physics, geosciences and inertial navigation. Until recently, light-pulse atom interferometry had only exploited continuous-wave (cw) laser sources. Here, I will present atom interferometers where the beam splitters are realized with pulsed lasers, or more specifically frequency-comb lasers [1]. This technique, which we demonstrated in the visible spectrum on rubidium (Rb) atoms, paves the way for extending light-pulse interferometry to other wavelengths (e.g. deep-UV to X-UV) and therefore to new species, since one can benefit from the high peak intensity of the ultrashort pulses which makes frequency conversion in nonlinear media efficient.

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F.3 Spin squeezing of dipoles enhanced by mobility

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Spin squeezing quantifies the reduction of quantum projection noise along a measurement axis, allowing for quantum sensing beyond the standard quantum limit. In experiments, spin squeezing is typically generated by collective interactions. Spin squeezing generated by short-range dipolar interactions provides an attractive alternative which is now entering experimental reach. A crucial challenge in this regard is identifying optimal parameter regimes for spin squeezing.

Dipoles trapped in deep optical lattices face off-resonant scattering of lattice light and low filling fractions as decoherence sources. While itinerant dipoles in harmonic traps can mitigate these limitations, they are fundamentally limited by collisional decoherence. Here, we propose shallow lattices as a way to combine the advantages of these two setups. Using exact matrix product state simulations for a chain of fermionic KRb molecules, we show that even in the presence of sub-unit filling and two-body losses 5dB of squeezing can be reached, outperforming deep lattices by up to more than 3dB. This enhancement is attributed to SU(2)-symmetric superexchange interactions, which give an energy penalty to leaving the collective manifold, thus protecting collective correlations. On the other hand, collision rates remain small due to on-site repulsion and the quantum Zeno effect.

We show that the optimal regime is achieved for small repulsive off-site interactions, with a trade-off between maximal squeezing and optimal squeezing time. Low filling fractions slow down the squeezing dynamics, but only slightly decrease the maximal attainable squeezing. We show that dephasing due to a differential trap depth between the two spin states can be mitigated by a dynamical decoupling pulse sequence.

F.4 Quantum enhanced ultra high sensitivity gravi-gradiometer

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The field of inertial sensors based on cold atom interferometry has known tremendous improvements during the last decade. They are one of the most mature quantum technologies and have reached sensitivities competing with conventional sensors. In this work, we present a cold atom gravi-gradiometer which measures the local value of the vertical component of g and its vertical gradient ∇g. This simultaneous measurement would benefit for resolving the ambiguity between detected weak mass and its localization.

Our sensor is based on two atomic clouds separated by one meter. The apparatus is magnetically shielded and probes simultaneously the gravitational acceleration. These atomic clouds are probed with common laser beams. Thus, the main advantage of this architecture is the rejection of common-mode noises - like vibration or laser phase noise - in the measurement of the gravity gradient ∇g. This common noise rejection paves the way to dramatic sensitivity improvements.

We discuss the recent implementation of multiphotonic Bragg beamsplitters dedicated to improve the gravi-gradiometer' scale factor. We also present the optimal control methods on Bragg diffraction to improve the efficiency of the matter-wave optics. These promising methods are of a great interest to improve the contrast of our sensor. Finally, we present a recent project of using atomic chip to efficiently prepare Bose-Einstein condensed atomic samples. These samples aim for implementing novel quantum metrology protocols for inertial sensing beyond the standard quantum limit.

The enhanced sensitivity of our sensor intends to significantly overcome the state-of-the-art gravi-gradiometers. This paves the way for new applications such as geophysics and onboard inertial sensing.

G Atom-like systems

G.1 Long spin and optical coherence times of Er sites in Si

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The exceptional properties of rare-earth ions in solid-state hosts at cryogenic temperatures make them a highly promising candidate for a range of applications, including optical quantum memories, optical-microwave transducers, and single dopant-based devices such as sources of single photons in the telecommunication band. Here, we present our recent results on the spin and optical coherence of Er ensembles in Si, probed using resonant photoluminescence excitation (PLE) spectroscopy. To conduct our measurements, we positioned Er implanted Si samples between a tailor-fabricated superconducting single photon detector and an optical fiber ferrule, all placed in a dilution refrigerator unit. Laser light for resonant excitation was delivered to the sample using fiber optics. This method enabled high collection efficiencies and spectral measurements of low Er densities. We also investigated the influence of co-dopants such as O, B or P on the observed Er PLE spectra, and found that they have a strong impact on the Er emission energies and Er sites formed. Notably, high densities of O resulted in particularly rich PLE spectra, indicating the presence of numerous Er-O complexes. In contrast, lower concentrations of O were found to result in a PLE spectrum dominated by a single Er site in P doped samples. We also discovered that Er spin relaxation properties were mainly influenced by the Er concentration. By reducing the Er concentration from 10^{18} cm^{-3} to 10^{16} cm^{-3}, we were able to significantly increase Er spin lifetimes from ~ 0.1 s to ~ 30 s. We also observed sub-MHz homogeneous linewidth was barely affected by the Er concentration. We observed sub-MHz spin transitions in both natural and isotopically purified Si, achieving spin coherence times above 1 ms in the latter. In terms of the optical coherence, we observed sub-MHz homogeneous linewidth only weakly affected by the Er concentration.

POSTERS

A Cold gases and quantum fluids

A.1 Many to few: From ultracold plasma to atom-ion hybrid systems

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Ultrashort laser pulses enable the local ionization of quantum gases on femtosecond timescales. By tuning the central wavelength of a single laser pulse of 166 fs duration across the two-photon ionization threshold of ^{87}Rb, we investigate the transition from ultracold plasma to dense Rydberg gases. Above the threshold photoelectrons from two-photon strong-field ionization are rapidly cooled and an ultracold plasma is formed. Below the ionization threshold a dense Rydberg gas is created due to the large bandwidth of the femtosecond laser pulse which circumvents the Rydberg blockade effect. Molecular dynamics simulations give us insight into the underlying dynamics dominated by long-range Coulomb interactions on picosecond timescales. Our setup allows direct detection of Rydberg states as well as the energy distribution of electrons and ions taking part in the many-body dynamics.

This detection will be enhanced in a novel coincidence unit consisting of a high-resolution ion microscope and a Velocity-Map-Imaging (VMI) spectrometer allowing for simultaneous resolution of the spatial distribution of the ions and the momentum of the photoelectrons. Optimization using a genetic algorithm results in a simulated resolution in the range of 100 nm, surpassing the optical resolution limit of quantum gas microscopes. The VMI spectrometer is designed to detect electrons with a kinetic energy of 0.05 meV - 3.2 eV, with a simulated resolution of $\Delta E/E \leq 10\%$. Additionally, a pulsed extraction of the ions and electrons grants access to a coincidence detection for investigating correlations as well as the time-resolved dynamics of the many-body system.

A.2 Coherence of confined matter in lattice gauge theories at the mesoscopic scale

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Gauge theories arise in physical systems displaying space-time local symmetries. They provide a powerful description of important realms of physics ranging from fundamental interactions to statistical mechanics, condensed matter and more recently quantum computation. As such, a remarkably deep understanding has been achieved in the field. With the advent of quantum technology, lower energy analogs capable to capture important features of the original quantum field theories through enhanced control quantum simulation have been intensively studied. Here, we study lattice gauge theories constrained to mesoscopic spatial scales. To

this end, we study the dynamics of mesons residing in a ring-shaped lattice of mesoscopic size pierced by an effective magnetic field. We demonstrate that, in these conditions, mesons are characterized by a dynamics with unique features. We find a new type of Aharonov-Bohm oscillations reflecting the coupling between the magnetic field and the internal structure of the meson. The coherence properties of the meson are quantified by the persistent current and by specific features of the correlation functions. When the magnetic field is quenched, Aharonov-Bohm oscillations and mesoscopic features of the meson current and correlations start a specific dynamics.

A.3 Density and pseudo-spin rotons in a bilayer of Rydberg-dressed bosons

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We study the dynamics of a bilayer system of bosons with repulsive soft-core Rydberg-dressed interactions within the mean-field Bogoliubov-de Gennes approximation. We find roton minima in both symmetric and asymmetric collective density modes of the symmetric bilayer. Depending on the density of bosons in each layer and the spacing between two layers, the homogeneous superfluid phase becomes unstable in either (or both) of these two channels, leading to density and pseudo-spin-density wave instabilities in the system. Breaking the symmetry between two layers, either with a finite counterflow or a density imbalance renormalizes the dispersion of collective modes and makes the system more susceptible to density-wave instability.

A.4 Optically trapped DyK Feshbach molecules near quantum degeneracy

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Ultracold heteronuclear Fermi-Fermi mixtures provide a unique platform to explore exotic regimes of superfluidity in mass-imbalance fermion systems [1]. Feshbach dimers consisting of two fermionic constituents are composite and can thus in principle form molecular Bose-Einstein condensates. Here, we report on the creation of Feshbach molecules of ^{161}Dy^{40}K near a well-isolated 7-G Feshbach resonance [2]. These molecules have a large magnetic moment (> 8.3 Bohr magneton), which allows us to selectively prepare them in a weak optical dipole trap (ODT) using a Stern-Gerlach technique. We estimate the phase-space density of the trapped molecules to be 0.13, which is already close to the degenerate regime. Furthermore, we study the lifetime of the molecular sample and identify single-molecule losses induced by the trap light as the dominant mechanism of losses. We find that the loss depends sensitively on the particular wavelength of the ODT light. We could suppress losses by replacing the 1064-nm laser originally used for the trap by a laser operating further in the infrared (near 1550 nm), and by tuning to a loss minimum. We observe further loss suppression by tuning the magnetic field close to the center of the Feshbach resonance. This suppression can be explained by the reduced close-channel fraction of the molecular wave function. With all these improvements we reach lifetimes of about $\sim$100 ms. Here elastic collisions dominate over inelastic collisions and the conditions are promising for further evaporative cooling to create a Bose-Einstein condensate of heteronuclear molecules.

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A.5 Beyond universality in repulsive SU(N) Fermi gases

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Itinerant ferromagnetism in dilute Fermi gases is predicted to be at values of the gas parameter where second-order perturbation theory is not accurate enough. We have revisited perturbation theory up to third order for SU(N) fermions and found its generalization in terms of both the gas parameter and the polarization. Our results agree satisfactorily with quantum Monte Carlo results for hard-sphere and soft-sphere potentials, both for s = 1/2. The nature of the transition highly depends on the interaction potential, however, for certain potentials such as hard-sphere we can guarantee that a phase transition occurs. While for s = 1/2 we observe a quasi-continuous transition, for spins 3/2 and 5/2, a first-order phase transition is found. For larger spins, a double transition (combination of continuous and discontinuous) occurs. The critical density reduces drastically when the spin increases, making the phase transition more accessible to experiments with ultracold dilute Fermi gases. Estimations for Fermi gases of Yb and Sr with spin 5/2 and 9/2, respectively, are reported.

A.6 All optical switching in a three-level V-type atomic medium based on electromagnetically induced transparency

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We use electromagnetically induced transparency (EIT) to generate optical switching of the probe laser field according to the modulation of the coupling laser field in a three-level V-type atomic system. When the absence of the coupling laser field, the probe laser field is completely absorbed by the atomic medium at the resonant frequency. However, the probe laser field becomes transparent (EIT) when the coupling laser field is present. Thus, by turning the coupling laser field ON or OFF, the output signal of the probe laser field is also switched from ON to OFF, and vice versa. To describe this optical switching phenomenon, we derive a set of Maxwell-Bloch equations for the three-level V-type atomic system with laser fields and use the 4th-order Runge-Kutta numerical method to simulate the propagation of the probe and coupling laser pulses in the atomic medium. Under the EIT condition, we obtain the optical switching of the probe signal modulated according to the coupling laser field. The influence of the switching period as well as the intensity and frequency of the coupling laser field on the optical switching of the probe laser field are also studied in this work.

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A.7 Making statistics work: a quantum engine in the BEC-BCS crossover

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We present a new class of many-body quantum engine that we termed Pauli engine. Our engine exploits genuine nonclassical forms of energy different from heat, which have not been used until now for work production in cyclic engines. In the Pauli engine the energy input is not related to the temperature of an external bath, instead, our machine is fueled by the energy associated with the change of the statistical behavior of the working medium from bosonic to fermionic and back. This mechanism is of purely quantum origin and has no correlate in the classical regime. Since the change in quantum statistic does not require the coupling to a hot or cold reservoir, the main advantage of the Pauli engine is that it is free of the dissipation processes of conventional engines. We experimentally realized the Pauli cycle by driving a trapped ultracold two-component Fermi gas of ^{6}Li atoms between a Bose-Einstein condensate of bosonic molecules and a unitary Fermi gas. Such experiments result in a work output of several 10^6 vibrational quanta per cycle with an efficiency of up to 25%. Our findings establish quantum statistics as a useful thermodynamic resource for work production in a new class of emergent quantum engines.

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A.8 Self-Pinning Transition of impurities in a Bose-Einstein Condensate

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We show that a Tonks-Girardeau (TG) gas that is immersed in a Bose-Einstein condensate can undergo a transition to a crystal-like Mott state with regular spacing between the atoms without any externally imposed

lattice potential. We characterise this phase transition as a function of the interspecies interaction and temperature of the TG gas, and show how it can be measured via accessible observables in cold atom experiments. We also develop an effective model that accurately describes the system in the pinned insulator state and which allows us to derive the critical temperature of the transition.

We will also show how extending the above idea to multicomponent TG gases can lead to the spontaneous emergence of more complex crystal structures with antiferromagnetic order, and how finite interactions in the immersed component lead to additional superfluid phases.

A.9 Realization of an atomic quantum Hall system in four dimensions

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Modern condensed matter physics relies on the concept of topology that is used to classify matter in topological classes. The physical properties of topological systems can be revealed with ultracold atoms, using rotating bose einstein condensates, modulated lattices or synthetic dimensions. Synthetic dimensions are of particular interest since they permit to simulate systems featuring both a bulk and edge states or to engineer periodic boundary condtions. They can also give acces to topological states in dimensions $D > 3$.

Recently, we realized a 4D quantum Hall system with ultracold Dysprosium atoms, using two spatial (x, z) and two synthetic dimensions (m, n) encoded in the large spin of Dysprosium atoms. An artificial magnetic field is generated using laser beams, in Raman configuration, that couple the spatial and spin degrees of freedom. For the laser power we use, one can show that our system is equivalent to the direct sum of a pair of 2D Landau levels.

We revealed the non-trivial topology of our system by measuring the quantized electromagnetic non-linear response. We measured in the bulk a local Second Chern marker equals to unity, which demonstrates the topological quantization. Topological properties are also revealed at the edges of our system, where we were able to measure anisotropic hyperedge modes : motion being balistic in one dimension and frozen in the two others. These anisotropic hyperedges are a marker of the 4D aspect of our system. We finally measured the cyclotron orbits in our 4D system, that can be non-planar contrary to their 2D-3D counterparts. Our work paves a way towards the study of interacting quantum many-body physics in high-dimensional topological structures.

A.10 Production of a $v_X = 0$ Rb_2 supersonic beam by optical pumping

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In this work, we report the production of a $v_X = 0$ Rb_2 supersonic beam starting from a hot vibrational molecular beam by optical pumping using a spectrally shaped broadband light source. Optical transitions from the $X^1\Sigma_g^+(v_X \geq 1)$ ground state to the $B^1\Pi_u$ excited potential can be driven by such source, which consists of several multimode diode lasers, in the $14730 - 14350$ cm^{-1} range, allowing population to be pumped to the

$X^1\Sigma_g^+(v_X = 0)$ state. The spectral shaping is done using a $4F$ diffraction grating configuration and a digital micromirror device. The molecules were detected by photoionization technique, through transitions from the $X^1\Sigma_g^+ \rightarrow B^1\Pi_u$ using a pulsed dye laser, at the $680 - 685$ nm range, and then photoionized by a 532 nm pulsed laser 5 ns later. Rb_2^+ spectra show that most of the molecules are pumped to $v_X = 0$. We have used this vibrationally cold molecular beam to perform spectroscopy of the $C^1\Pi_u$ potential. Simulations indicate that a rotational cooling can be accomplished by improving the spectral shaping scheme using a diffraction grating and a virtually imaged phase arrays in the $4F$ system.

A.11 Quantum Aubry transition in chains of long-range interacting particles

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We theoretically analyse the ground state of the Frenkel-Kontorova model where the particles interact via repulsive power-law forces. We show that the classical ground state can be mapped to the one of a long-range, antiferromagnetic Ising model and is a complete devil staircase as a function of the discommensuration. We then show that in the full quantum limit the commensurate-incommensurate transitions is described by the Thirring model with power-law interactions. We analyse the mean-field phase diagram for Coulomb chains and in relevant experimental regimes and determine the relevant spectroscopic features signalling the transition.

A.12 Expansion of a quantum gas onto the curved surface of an ellipsoid

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We report the observation of the controlled expansion of a two-dimensional Bose-Einstein condensate confined onto a curved shell-shaped surface. We start from the ellipsoidal geometry of a magnetic quadrupole trap dressed by radio-frequency and introduce a novel gravity compensation mechanism enabling to explore the full ellipsoid. Instead of the spreading of the atoms on the whole shell, one observes a continuous transition from an oblate shape of the atomic distribution to an annular ribbon. This phenomenon highlights the essential role of the zero-point energy of the transverse confinement, and the experimental results are compared with the solution of the three-dimensional Gross–Pitaevskii equation and with a 2D semi-analytical model refined with beyond rotating-wave approximation terms. This work evidences how a hidden dimension can affect dramatically the embedded low-dimensional system by inducing a change of topology. It also shows how accurate the control of the polarization of the dressing field has to be in a gravity-compensated environment, and the intrinsic limitations to an uniform atomic distribution on closed surfaces in similar systems. Due to its great smoothness

and long lifetime, this gravity-compensated dressed trap is promising to study superfluid dynamics in a curved environment.

A.13 Preparing spin textures of SU(N) Fermions in optical lattices

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Ensembles of large-spin atoms offers the potential to study quantum magnetism beyond what is possible with effective spin-half atoms. The aim of our experiment is to study magnetic order and out-of-equilibrium dynamics of ultracold degenerate Fermi gases arranged in periodic potentials induced by lasers. For this purpose, we use Fermionic strontium with a spin of $F = 9/2$ that has spin-independent collisional property. I will describe our experimental approach of the initialization of states to study out-of-equilibrium dynamics. We prepare polarized Fermi gases in one spin state of the 87Sr ground state by optical pumping. I will describe how this gas is then loaded into an anisotropic spin-independent optical lattice that creates several 2D planes, where each plane corresponds to a quasi 2D gas with zero spin entropy. Then a two photon Raman transition between two spin states enables us to control the final spin state deterministically. Spin state selectivity is done by creating tensor light shifts between two spin states. We show that we can measure the spin population of a given state by spin-selective momentum transfer technique [1]. Our current focus is to write spin textures with spatially inhomogeneous spin-dependent potentials. Starting from these low entropy spin textures we can study the out-of-equilibrium dynamics of these many body states. I will describe our recent advances towards this goal. Our experiment is further scalable up to a 10 spin state ensemble, which should provide insights related to entanglement and magnetism in an SU(N) symmetric system.

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A.14 A new Lithium 6 Quantum Gas Microscope: Exploring the Projection of a Many-Body Wavefunction into Single Atoms

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The quantum gas microscope is a powerful tool that allows to probe dilute quantum matter with single atom resolution, and has proven extremely useful for analog quantum simulation of lattice and spin-chain Hamiltonians. Here we report on the realization of a Lithium 6 quantum gas microscope devoted instead to the study of Fermi gases in continuous space and explore the projection dynamics from an initial many-body wavefunction onto individual lattice sites. This new "continuous space quantum gas microscope" offers the

perspective to probe strongly interacting Fermi gases and topological quantum matter at an unprecedented length scale.

A.15 Vortex Pair Dynamics in Three-Dimensional Homogeneous Dipolar Superfluids

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The recent observation [1] of quantum vortices in a Bose-Einstein condensate (BEC) of dysprosium has opened up new experimental avenues into studying the interplay of the anisotropic, long-ranged dipolar interaction and the fundamental aspects of superfluidity. Whereas the density profiles of vortices in dipolar BECs have been studied theoretically in harmonically trapped [2] or quasi-two-dimensional systems [3], the advent of so-called box potentials merits an investigation of vortex states in the homogeneous, three-dimensional regime. By assuming an arbitrary dipole polarisation and relaxing the assumption of incompressibility, we find that, when the vortex and dipoles are not parallel, the ground states of single vortices in this system are anisotropic in not only the density – as predicted previously [2,3] – but also the superfluid phase. This arises as a consequence of the screening of the dipolar interaction by virtual dipolar 'holes' [4] in the vortex core. In accompanying theoretical simulations of the dynamics of like-signed and opposite-signed vortex pairs, the anisotropy also causes dipole-mediated deviations of the dynamics away from the well-understood point-vortex limit. While certain aspects of these results had been predicted in dipolar BECs in three-dimensional harmonic traps [2] and in quasi-two-dimensional systems [3], our studies suggest that these effects are not due to the confinement of the gas but are an intrinsic feature of dipolar superfluids with experimentally verifiable signatures in vortices generated in three-dimensional box potentials [5]. We also note that these results may have consequences for the dynamics of vortex reconnections and quantum turbulence in dipolar Bose gases.

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A.16 Precision measurement of atom-dimer interaction in a uniform planar Bose gas

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We perform microwave photoassociation of ultracold 87Rb atoms to create weakly bound dimers of pairs of atoms in the hyperfine levels F=1 and F=2 of its electronic ground state. We detect these dimers by losses of atoms in the cloud. Our experimental platform of planar and uniform Bose gases, avoiding the inhomogeneous broadening of the signal, allows us to have a precision on the frequency of the MW transfer on the order of a few kilohertz. We first measure the full Zeeman diagram of the relevant hyperfine manifold for the least-bound dimer level. We then show that the central frequency of the MW field, used to create the dimer, depends linearly on the atomic density of the bath. We interpret this shift within a mean-field approach which allows us to extract a scattering lenght for the atom-dimer interactions.

A.17 Dark states potentials and bands for ultra cold atoms

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A scheme to create optical potential for ultra cold atoms by restricting them to position-dependent dark state has been proposed in [1]. This approach, in contrast to standard AC-Stark shift based optical potential allows to create potentials with sharp spatial features. It also involves optical potentials for atoms populating a coherent position-dependent superposition of atomic states. In this poster I present the extension of the original work: creating the lattice systems with high Chern number (dark states that superpose Bloch states of topological bands), atomic dark states in the tripod-like configuration, generating random potentials as a dark state potentials and perspectives for studying Anderson localisation.

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A.18 Subradiance in ordered ensembles of Dysprosium atoms

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My poster will present my experimental work on a setup we are currently still building. We propose to create dense arrays of dysprosium atoms with the goal of observing sub-radiance : reduced spontaneous emission. For this we will take advantage of the rich atomic structure of dysprosium. We use narrow line cooling, then single atom optical tweezers which have been adapted to this new atom. Then we will transfer the atoms towards a variable lattice spacing optical lattice on magic wavelength. We will then study sub-radiance in the resulting dense and ordered ensemble of dysprosium atoms as well as the emergence of atomic correlations in the presence of collective spontaneous emission.

A.19 Ionic polarons and bipolarons in an ultracold Bose gas

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We investigate the static properties of one and two ionic impurities immersed in a bosonic atomic bath at zero temperature using ab initio many-body quantum Monte Carlo as well as modified mean field approach. Several regimes are identified depending on the strength of the atom-ion potential and the number of its two-body bound states. In particular, a many-body bound state can form, consisting of hundreds of strongly correlated particles with nonperturbative induced interactions between two such clusters. Our findings show that numerical simulations are indispensable for describing highly correlated impurity models for which the pseudopotential approximation cannot be made.

A.20 Brillouin spectroscopy of metastable superfluid helium-4

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Because liquid helium at low temperature is the purest possible liquid, it is a model system to probe deep condensed matter metastable states and homogeneous nucleation phenomenons in quantum fluids. Homogeneous nucleation theory is a cosmological issue as it could apply to possible phase transitions in the early universe. The absence of impurities and the little thermal energy available in the fluid make of superfluid helium-4 an appealing candidate to reach experimentally the close vicinity of the spinodal limit where the compressibility of the liquid diverges making it mechanically totally unstable even in the limit $T \to 0$.

Our experiment produces metastable (negative pressure) states of superfluid ^{4}He by focusing acoustic waves within the bulk of the liquid. Recently, we have developed and implemented a finely spatially and temporally resolved stimulated Brillouin spectrometer capable of measuring optically the compressibility of the metastable states of superfluid helium-4. This has enabled us to estimate the destabilization (cavitation) pressure of liquid ^{4}He at 1 K. Our results clearly disagree with previous estimates made by more indirect methods than ours and suggest that the quantized vortices of the superfluid could serve as phase nucleation sites for the cavitation bubbles [1].

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A.21 Bose-Hubbard triangular ladder in an artificial gauge field

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We consider interacting bosonic particles on a two-leg triangular ladder in the presence of an artificial gauge field. We employ density matrix renormalization group numerical simulations and analytical bosonization calculations to study the rich phase diagram of this system. We show that the interplay between the frustration induced by the triangular lattice geometry and the interactions gives rise to multiple chiral quantum phases. Phase transition between superfluid to Mott-insulating states occur, which can have Meissner or vortex character. Furthermore, a state that explicitly breaks the symmetry between the two legs of the ladder, the biased chiral superfluid, is found for large values of the flux. In the regime of hardcore bosons, we show that the extension of the bond order insulator beyond the case of the fully frustrated ladder exhibits Meissner-type chiral currents.

A.22 Self-bound Fermi-Fermi mixtures in 1D

Andrea Tononi[1], J. Givois[1], D. S. Petrov[1]

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Self-binding in Bose-Bose mixtures has received lots of theoretical [1] and experimental [2] attention in the recent years, and a few studies discussed also Bose-Fermi droplets [3]. Fermi-Fermi mixtures with interspecies attraction, however, are not expected to display self-bound states, since the fermions of one species should overcome a strong Pauli pressure to bind the fermions of the other. This repulsion is, in fact, the fundamental mechanism that provides stability of Fermi mixtures along the BCS-BEC crossover, whose dimers repel and do not form larger clusters [4].

In our recent work [5] we find that one-dimensional Fermi-Fermi mixtures with sufficiently large mass imbalance can form a self-bound state in the thermodynamic limit. This result elaborates our previous few-body analyses [6], and is based on a mean-field theory in which the heavy fermions are described within the Thomas-Fermi approximation, which is exact in the limit of large mass ratios. Our work sets the basis for future studies of self-bound fermions in higher-dimensional cases, which can shed light on the fundamental behavior of macroscopic fermionic aggregates.

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A.23 Thermal fading of the $1/k^4$-tail of the momentum distribution induced by the hole anomaly

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We provide the ab-initio Path Integral Monte Carlo calculation of the momentum distribution in a one-dimensional repulsive Bose gas at finite temperatures. We explore all interaction and thermal regimes. An important reference temperature is that of the hole anomaly, observed as a peak in the specific heat and a maximum in the chemical potential [1]. We find that at large momentum k and temperature above the anomaly threshold, the universal tail C/k^4 of the distribution (proportional to the Tan's contact C) is screened by the $1/|k|^3$-term due to a dramatic thermal increase of the internal energy. The same fading is consistently revealed in the short-distance behavior of the one-body density matrix (OBDM) where the $|x|^3$-dependence disappears for temperatures above the anomaly. At very high temperatures, the OBDM and the momentum distribution approach the Gaussian of classical gases. We obtain a new and general analytic tail for the momentum distribution and a minimum k fixing its range of validity, both calculated with Bethe-Ansatz and valid for any interaction strength and temperature [2].

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A.24 Optically induced lattices in rubidium vapor

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Experimental realizations of non-Hermitian systems have lately increasingly branched out from solid-state systems to atomic gases, where an interfering pair of pump beams interacts with the atoms in the gas thus producing an array of waveguides for the probe beam. We investigate this optically induced lattice in a three-level Λ-type system in ^{87}Rb vapor where the pump and probe beams are tuned to the ^{87}Rb D_2 resonance at 780 nm. We observe a discrete diffraction pattern of the probe beam, as well as shifting of the probe diffraction pattern maximum from the pump lattice maximum to the lattice minimum as the probe frequency is scanned. We discuss the potential of introducing an additional pair of pump beams to create a four-level N-type system that would, aside from the spatially modulated refractive index, enable the realization of a spatially modulated gain, and thus enable the study of discrete diffraction dynamics on optically induced lattices with periodic gain and loss profiles.

A.25 Self-binding in one- and two-dimensional mass-imbalanced fermionic mixtures

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In the last 10 years, the few-body bound states made of 1 light fermion interacting attractively with N heavy fermions were analyzed in all spatial dimensions. To address the large N limit and to investigate the formation of $N+1$ clusters in one-dimensional fermionic mixtures with weak attraction, we developed a mean-field approach based on the Thomas-Fermi approximation for the heavy atoms kinetic energy. If extended to the thermodynamic limit, our method predicts the binding of such $N+1$ clusters into a self-bound charge-density wave, a counterintuitive phenomenon which was not expected to occur due to the large Pauli pressure of the system. Recently, we have extended our method to describe the two-dimensional case, in which the formation of bound states is complicated by the same scaling with length of the kinetic energy and of the interaction energy of the system. Nonetheless, similarly to the 1D case, we find that the 2D case can be described with a single parameter that combines the mass-ratio and N, and we are also able to analyze both the $N+1$ clusters and their binding.

A.26 Binary supersolids in dipolar condensate mixtures

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Two-component dipolar condensates are now experimentally producible, and we theoretically investigate the nature of supersolidity in this system. We predict the existence of a binary supersolid state in which the two components form a series of alternating domains, producing an immiscible double supersolid. Remarkably, we find that a dipolar component can even induce supersolidity in a nondipolar component. In stark contrast to single-component dipolar supersolids, alternating-domain supersolids do not require quantum stabilization, and the number of crystal sites is not strictly limited by the condensate populations, with the density hence being substantially lower. Our results are applicable to a wide range of dipole moment combinations, marking an important step towards long-lived bulk supersolidity.

A.27 A Multipurpose Lithium-6 Platform for Analog Quantum Simulation

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Atom-based quantum simulators have had tremendous success in tackling challenging quantum many-body problems, owing to the precise and dynamical control that they provide over the systems' parameters as well as their rich toolbox of techniques. Most quantum gas experiments, however, are optimized to address a specific type of problems, which constitutes a limitation from the perspective of wide-scope quantum simulation. Here,

we present a design for a Lithium-6 based quantum gas platform that provides wide-ranging capabilities and is able to address a variety of quantum problems that have historically been treated on different setups. Our two-chamber architecture relies on robust and easy-to-implement techniques, allowing us to produce ultracold ensembles of interacting fermions and place them in a broad range of energy landscapes, from continuous space in 1D, 2D and 3D, to single- and multi-layered lattices. With the ability to probe quantum many-body physics in both discrete and continuous space through bulk as well as single-atom imaging, our setup represents an important step towards achieving a wide-scope atom-based quantum simulator.

A.28 Sensing interactions in atomic quantum systems

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Experiments that cool, trap, and control atoms, ions, and molecules provide a unique testbed. Hybrid ion-atom systems combine the well-controllable platforms of trapped ions and ultracold quantum gases and link them together by the intermediate-range ion-atom interaction. These quantum systems offer opportunities for buffer gas cooling, quantum simulation of many-body systems as well as for state-to-state quantum chemistry [1]. To fully benefit from the combination, it is essential to understand, characterize, and control the interactions between the atoms and ions. Therefore, at TU/e a new experimental setup is being build which combines a trapped ion – Yb^+ - with dipolar atoms - Dy. This poster reports on the development of its design and how it can be used to sense interactions in these atomic quantum systems.

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A.29 State-selective charge exchange in ion-molecule and three-body recombination in ion-atom-atom rubidium systems at the ultracold temperatures

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We study the interactions between two Rb atoms and one Rb^+ ion from a quantum chemistry perspective, considering the Rb_2+Rb^+ and Rb_2^++Rb arrangements. These interactions are relevant for the fundamental chemistry, sympathetic cooling, and three-body recombination (TBR) processes at ultra-low temperatures observed in hybrid ion-atom experiments for homo- and hetero-alkali ion-atom species, with Rb^+ (or Ba^+,

Ca^+)+Rb+Rb. Formation of Rb_2^+ has recently been observed in inelastic collisions of a single cold Rb^+ in a BEC of Rb atoms [1,2]. Another experiment has reported probable formation of molecular Rb_2 in an hybrid ion-atom trap [3]. We start by calculating the electronic structure of the Rb_3^+ ion using various approaches involving both large-core and small-core effective core potentials. We find that for specific geometry configurations, state-selective charge exchange reactions would occur for the ion-molecule Rb^++Rb_2 system. We extend our investigations toward the large distance domain to elaborate on the transition from atom-molecule to three-atom configurations relevant to TBR, which could be responsible for molecular collision products Rb_2^+ and Rb_2. We show the generalization of these results for any alkali homo-nuclear three-body ion-molecule and ion-atom-atom systems.

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A.30 Cavity-assisted dispersive interaction of cold atoms with a frequency comb

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Conventional laser cooling of atoms relies on spontaneous emission of near-resonant light. Many cycles of optical pumping are needed to efficiently cool the atoms, which is why atoms with closed transitions are necessary. If an atom decays into a different ground state, many repumping lasers are needed to keep the process efficient, which is the main issue in practical cooling of most atomic species and molecules, which posses ro-vibrational levels.

On the other hand, for atoms located in a high-finesse optical cavity, photon loss through the cavity mirrors can serve as a dissipation mechanism responsible for cooling [1]. In this cavity cooling technique, cooling is achieved through dispersive interaction of atoms and cavity light, which makes it insensitive to the energy structure of the cooled particles. However, for deep enough cavity potentials the atoms localize in the potential minima, which increases the cooling time and makes the technique impractical. To circumvent this limitation, we couple a frequency comb (FC) to the cavity. Given that the FC spectrum coincides with the cavity spectrum, a simultaneous interaction of atoms with multiple cavity modes can be achieved and a complex multi-mode intracavity potential can be created [2].

We report on the first experimental observation of collective dispersive interaction of cold ^{87}Rb atoms inside an optical cavity with FC light. This dispersive effect is seen as enhancement or suppression of transmitted FC light due to FC interaction with an ensemble of atoms inside the cavity. Additionally, we observed for the first time squeezing and broadening of atomic distribution in time-of-flight images, a signature of dispersive cavity-assisted cooling and heating of atoms with an FC.

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A.31 Charge and pair density waves induced by light in a strongly interacting Fermi gas

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Quantum gas experiments provide the unique opportunity to create and study complex quantum many-body systems. Starting from a dilute gas, interactions can be added in a controlled way using Feshbach resonances. Furthermore non-local, all-to-all interactions can be implemented by means of a high-finesse optical cavity [1].

In our experiment, we prepare a strongly interacting Fermi gas of Li 6 atoms cooled down to the degenerate regime, trapped inside a high-finesse optical cavity [2]. In this system both contact and cavity-mediated interactions are independently controlled [3], allowing for the study of density-wave ordering in the BEC-BCS crossover [3]. In particular we study the dynamics of the transition as we ramp at finite speed or quench into the density-wave ordered phase, and observe the onset of order in real time for a wide range of parameters.

Furthermore, by operating this scheme close to a photoassociation transition [4], realizing an optical Feshbach resonance, we induce long-range, atom-pair and pair-to-pair interactions mediated by cavity photons. We observe the density-wave ordering phase transition in the presence of these interactions, suggesting a pair-density-wave state of the gas. We characterize the transition threshold and the lifetime of this state as we vary the strength and sign of the photoassociation coupling.

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A.32 Imaging of individual ions via Stark shift-induced photoabsorption

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Cold hybrid ion-atom systems are promising for understanding the physics of impurities with possible studies of charge mobility, ion-atom reaction, and polarons physics. Studying the dynamics of impurity ions will benefit greatly from a non-destructive and fast imaging technique. In this report, I will show how Rydberg atoms can be used for probing and imaging the electric field created by ions embedded in an atomic gas, allowing for the fast detection of the ions [1].

Rydberg energy levels of atoms are subject to huge Stark effects in the vicinity of an ion. When the ion-atom mixture is being driven in condition of electromagnetically induced transparency (EIT) involving a Rydberg state, the ions within the atomic cloud induce enhanced scattering of the probe light in their surrounding due to a phenomenon similar to photon blockade. While simple shadow imaging of the probe light was employed for imaging the ions in our previous work [1], a recent improvement making use of homodyne detection with a strong reference beam allows us to realize imaging in a single shot with only one microsecond exposure time [2].

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B Quantum optics, quantum information and quantum simulation

B.1 Quantum Optics with thermal vapours in the hyperfine Paschen-Back regime

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Single photon sources are highly sought after because photons are excellent quantum information carriers, and are important for quantum communication and fundamental quantum optics [1]. We carry out four-wave mixing using a ladder energy level system on the $5S_{1/2}$-$5P_{3/2}$-$5D_{5/2}$ states of thermal ^{87}Rb vapour, to produce a heralded single photon source. We measure a heralded auto-correlation value of $g^{(2)}(\tau = 0) = 0.25 \pm 0.02$ for this source, which is non-classical. We also place the vapour in a 0.6 Tesla magnetic field to implement this scheme in the hyperfine Paschen-Back regime, where the transitions are separated by more than their width, which allows for a cleaner system. We use this cleaner system, in combination with a highly tuneable lens cavity filter [2], to investigate the fine-structure changing buffer gas collisions which are a source of noise in this

experiment. Finally, we use the large magnetic field regime, in which π and σ transitions are frequency resolved, and π transitions can only be excited when $\vec{E}$ is parallel to $\vec{B}$, as a method of observing the z component of the electric field.

B.2 Sideband Thermometry on Ion Crystals

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Being a prospective platform for quantum computing and metrology, Coulomb crystals of ultracold trapped ions currently reach sizes of hundreds of individual particles. Such systems require high level of control over their motional temperature in order to account for the second-order Doppler shift in atomic clocks and implement high-fidelity entangling gates in quantum computers. However, the existing ion crystal thermometry tools struggle to provide an accurate temperature estimation for large ground-state cooled Coulomb crystals, either focusing only on the symmetric center-of-mass vibrational mode of motion or neglecting the involved spin-spin correlations between the trapped ions.To resolve the arising thermometry bottleneck, we consider the many-body dynamics of an ion crystal, arising when motional sideband transitions are driven in a near ground-state regime. In the single ion case, thermometry methods based on the motional sidebands are widely used and are thus of interest in the ion crystal case. The conducted study of the single-ion case from the Fisher Information prospective gives us some valuable insights for extending the approach further towards ion crystals. In our work we account for entanglement created between the ions in a Coulomb crystal to derive a new reliable temperature estimator, insensitive to the number of ions, and field-test in experiments with 4- and 19-ion crystals done by our colleagues from PTB Braunschweig and University of Innsbruck.

B.3 Multiple polaritonic edge states in a Su-Schrieffer-Heeger chain strongly coupled to a multimode photonic cavity

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A Su-Schrieffer-Heeger chain of dipoles strongly coupled to a multimode cavity is studied. By integrating out the photonic degrees of freedom of the cavity, the system is recast in a two-band model with an effective long-range coupling. The strong light-matter interaction leads to an unusual closing of the topological band gap at the center of the Brillouin zone, resulting in an additional topological phase transition neither associated with the appearance nor the disappearance of edge states. Multiple polaritonic edge states are observed, arising from polaritons entering in resonance with the dipolar topological edge states, and inheriting their localization properties. Although these states are not fully localized and have a participation ratio which depends on the system size, they present unusual properties. In particular, due to their delocalized bulk part, owing from their polaritonic nature, such edge states exhibit excellent transport characteristics.

B.4 Disorder-enhanced transport in a chain of lossy dipoles strongly coupled to cavity photons

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Over the past several years, strong coupling of matter excitations with confined electromagnetic modes has been shown to significantly modify material properties. Notably, polaritonic excitations are known to exhibit long-range energy transport characteristics. Moreover, while Anderson localization suppresses transport in one-dimensional systems with short-range interaction [1], such hybrid light-matter excitations have been proven robust against disorder [2]. Surprisingly, in recent studies of disordered polaritonic systems [3,4], an improvement of the transport characteristics has been observed when increasing the disorder strength, instead of the expected suppression. The interplay between disorder and strong light-matter coupling is then highly nontrivial, and its understanding is of primary importance, since disorder is always present in experimental setups.

In this work, we study such interplay by considering a disordered one-dimensional chain of lossy dipoles coupled to a multimode optical cavity through a microscopically-derived Hamiltonian. Such a disordered system hosting polaritonic excitations may be realized experimentally in a wide range of systems with strong light-matter coupling, from plasmonic and dielectric nanoparticles to ultracold atoms or molecules embedded in a photonic cavity.

By analyzing both the eigenspectrum and the driven-dissipative transport properties of our system, we find that in the strong-coupling regime, increasing disorder leads uncoupled dark states to acquire a photonic part, allowing them to inherit polaritonic long-range transport characteristics. Crucially, we show that this disorder-enhanced transport mechanism is increasingly noticeable when the considered dipoles are lossier.

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B.5 X-ray Waveguide QED with Mössbauer Nuclei

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Grazing incidence X-ray waveguides have become a well established platform for X-ray quantum optics. In these systems, X-rays are scattered resonantly by Mössbauer transitions in atomic nuclei. Due to the indistinguishability of the nuclei and the recoil-free Mössbauer transititions, the collective emission and absorption of

radiation plays a large role. Recently a formalism has been developed to describe the collective nuclear response using the classical electromagnetic Green's function for the waveguide [1,2]. However, so far these works have considered only translationally symmetric systems, and plane wave driving fields. In this regime, the spatial structure of the nuclei in the direction of propagation is insignificant, and pure single mode Dicke super-radiance is observed.

We show that driving the waveguides at forward incidence instead allows for direct excitation of multiple guided modes, with centimetre scale attenuation lengths. In this regime, the embedded Mössbauer nuclei absorb and emit collectively into a super-position of these modes, with the resultant radiation field displaying pronounced interference beats on a micrometre scale. We show that this interference pattern leads to sub-radiance of the nuclear ensemble, with suppression of the dynamical beat at certain critical waveguide lengths. We also consider structuring the nuclear ensemble into micrometre scaled patches, and show that it is feasible to engineer the resultant inter-nuclear coupling to create mesoscopic hopping models, with potential for applications in quantum simulation and experimental exploration of mesoscopic quantum dynamics.

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B.6 Non-local Multi-qubit Quantum Gates and Entanglement Generation in Cavity

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Natively available high-fidelity non-local quantum operations can be advantageous in drastically decreasing the number of gates in implementation of quantum circuits in Noisy-Intermediate-Scale-Quantum(NISQ) era devices and also in enabling fault-tolerant quantum computing. In this regard, we present protocols for implementing deterministic non-local multi-qubit quantum gates on qubits coupled to a common bosonic mode e.g. a cavity field, and an excitation blockade protocol to prepare a multi-qubit entangled state. In contrast to previous proposals, our protocols only rely on a classical drive of the bosonic mode, while no external drive of the qubits is required. We show that the gate errors scale as $N/\sqrt{C}$ and the entangled state preparation error scales as $\sqrt{1-1/N}/\sqrt{C}$ where C is the cooperativity and N is the qubit number. Our protocols are applicable to a variety of systems, including cold atoms and molecules in cavities, trapped ions coupled via a motional mode, and superconducting qubits coupled to a microwave resonator.

B.7 Optical tweezers in trapped-ion quantum simulations

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Trapped ion crystals offer a natural platform for quantum simulation. They observe great advantages with regards to other systems, such as long coherence times ($\sim$ hours), fully connected interactions and triangular lattice crystalline structure. We generate an effective spin Hamiltonian by applying state-dependent Raman transitions on the ions, whose interaction is mediated by the crystal's phonon modes. However, limited control over this phonon spectra constrains the range of accessible Hamiltonians. We aim to significantly broaden this range by implementing a novel platform for quantum simulation on a 2D in crystal by using optical tweezers. The latter are used to manipulate the ion crystal's phonon spectrum. This adds additional degrees of tunability to the Hamiltonian. In addition, we describe a theoretical framework for the realisation of a fast geometric phase gate, combining optical tweezers with electric field pulses. The tweezers generate a state-dependent potential which modifies the phonon spectrum, and the electric-field pulses generate momentum kicks on the ions, which result in a shortening of the amount of time spent on secular motion during the gate, thus highly decreasing overall gate time.

B.8 Higher-order mean-field theory of chiral waveguide QED

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Waveguide QED with cold atoms provides a potent platform for the study of non-equilibrium, many-body, and open-system quantum dynamics. Even with weak coupling and strong photon loss, the collective enhancement of light-atom interactions leads to strong correlations of photons arising in transmission, as shown in recent experiments. Here we apply an improved mean-field theory based on higher-order cumulant expansions to describe the experimentally relevant, but theoretically elusive, regime of weak coupling and strong driving of large ensembles. We determine the transmitted power, squeezing spectra and the degree of second-order coherence, and systematically check the convergence of the results by comparing expansions that truncate cumulants of few-particle correlations at increasing order. This reveals the important role of many-body and long-range correlations between atoms in steady state. Our approach allows to quantify the trade-off between anti-bunching and output power in previously inaccessible parameter regimes. Calculated squeezing spectra show good agreement with measured data, as we present here.

B.9 Azimuthal Dependence of Electromagnetically Induced Grating in a Double V-type Atomic System near Plasmonic Nanostructure

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We have investigated the performance of an Electromagnetically Induced Grating (EIG) in a four-level quantum system located near a plasmonic nanostructure (PN). The PN consists of metal-coated dielectric nanospheres in a periodic 2D arrangement. The double V-type system is coupled by a weak probe laser, a spatially-dependent standing wave, and a Laguerre-Gaussian field. Our numerical simulations show that by varying the distance between the PN and the quantum system, the amplitude and phase modulations of the transmission function can be modified when the winding number of the vortex light is also altered. When the quantum system is placed close to the PN by adjusting the orbital angular momentum of the vortex light, most of the energy of the probe is transferred to the high order, while at larger distances most of this energy is converged in the zero order. Our work demonstrates a simple scheme for double control over the diffraction efficiency of the 2D grating by using both the winding number of the vortex field and the distance between the PN and the quantum system as control knobs. The proposed scheme is advantageous by providing easily achievable manipulation of the grating performance, while it can be realized in typical quantum optics experimental settings, involving, for example, hyperfine sublevels of D-lines in alkali-metal atoms.

B.10 Robustness of different modifications of the quantum random walk search algorithm

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One of the most important quantum random walk based algorithms is the Discrete Time Quantum Random Walk Search (DTQRWS) [1]. This algorithm, together with the Grover's search algorithm, can find an element in unordered database quadratically faster than the fastest classical search algorithms. Compared to Grover's algorithm, that is constructed to search in linear database, DTQRWS can search in a graph with arbitrary topology. DTQRWS is also used as a component in various quantum algorithms. In our previous works [2,3], we study DTQRWS on Hypercube with walk coin constructed by generalized Householder reflection and an additional phase multiplier. Our primary goal was to study the robustness of the algorithm with different functional dependences between phases – how probability to find solution changes when the functional dependence is not fulfilled. Our research methods include Monte-Carlo simulations together with supervised machine learning. They allow us to obtain the robustness of the algorithm for different functional dependences between the phases for coin sizes between 2 and 11. In addition, we make a prediction how the robustness will change when coin size is outside the region where simulations can be made. However, those works studied the robustness of the original QRWS algorithm when only the coins are modified. Here, we present our investigations for the robustness of different modifications of the DTQRWS algorithm and compare them with each other. By using numerical simulations, together with linear regressions, we make detailed analysis for the robustness in case of different coin sizes and functional dependencies between phases.

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B.11 Quantum Gate Optimization for Rydberg Architectures in the Weak-Coupling Limit

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We demonstrate machine-learning assisted design of a two-qubit gate in a Rydberg tweezer system. We use two low-energy hyperfine states in each of the atoms as the logical qubit, and a Rydberg state as an auxiliary state to induce qubit interaction. Utilizing a hybrid quantum optimizer, we generate optimal Rabi- and Raman-pulse sequences that implement a CNOT gate with high fidelity, for experimentally realistic parameters and protocols, as well as realistic limitations. We show that the strategies generated in this fashion are robust for both the strong-coupling, blockade regime of the Rydberg states, as well as for the weak-coupling regime. In particular, we show that Rydberg-based quantum information processing in the weak-coupling regime is robust and optimal with current technology.

B.12 Hilbert Space Engineering of Nuclear Spin Qudits

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There are many promising quantum computing (QC) platforms at varying levels of technological readiness, each presenting their own advantages and disadvantages. Here, our research is focused on quantum information processing (QIP) devices comprised of rare-earth (RE) single-molecule magnets (SMMs). In particular, the nuclear spins of lanthanide (Ln) based SMMs have experienced a surge of scientific interest in recent years. These systems have a number of favourable properties for QIP: The nuclear spin states exhibit long coherence times that are improved due to the environmental isolation afforded by the molecular ligand; the 4f valence electrons in the triply-ionized bound state provide useful means of electro-magnetic control; and the high-dimensional (qudit) Hilbert space of the individually addressable hyperfine levels enables novel computing applications. In collaboration with chemists of the Ruben Group, and experimental physicists of the Wernsdorfer Group, in Karlsruhe (KIT), the goal of this project is to further develop the QIP capabilities of these systems through theoretical modelling and numerical simulation, particularly regarding aspects of universality and scalability. The first step that we present is to obtain single-qudit universality by finding methods to decompose any arbitrary quantum gate $U \in SU(d)$ in sequences of elementary pulses. This can be done either by using analytical SU(d) decomposition methods, or by numerical optimisation of pulse parameters. Two optimal control techniques studied here are the GRAPE algorithm and Physics-Informed Neural Networks (PINNs). In an open-quantum systems approach, we investigate the resilience and robustness of these different techniques to control errors and environmental noise. As a second step, towards scalability, we are working on modeling systems of coupled nuclear molecular qudits, following experimental investigations. By simulating entangling gates over suggested coupling mechanisms and extending the aforementioned control techniques, this could

suggest a direction toward multi-qudit universality and universal quantum computation with these fascinating systems.

B.13 Towards realization of long-lived chains of circular Rydberg atoms for quantum simulation

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

B.14 Deterministic Wigner-negative photonic qubits (from an intracavity Rydberg superatom)

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Engineering quantum states of free-propagating light is of paramount importance for quantum technologies. Coherent states ubiquitous in classical and quantum communications, squeezed states used in quantum sensing, and even highly-entangled cluster states studied in the context of quantum computing can be produced deterministically, but they obey quasi-classical optical field statistics described by Gaussian, positive Wigner functions. Fully harnessing the potential of many quantum-engineering protocols requires using Wigner-negative states, so far produced using intrinsically probabilistic methods.

I will describe the first fully deterministic preparation of Wigner-negative free-propagating states of light. In our setup, a small atomic cloud placed inside a medium-finesse optical cavity and driven to a highly-excited Rydberg state acts as a single two-level collective superatom [1]. We map the internal state of the intracavity Rydberg superatom onto an optical qubit encoded as a superposition of 0 and 1 photons [2]. This approach allows us to reach a 60% photon generation efficiency in a well-controlled spatio-temporal mode, while maintaining a

strong photon antibunching. By changing the qubit rotation angle, we observe an evolution from quadrature squeezing to Wigner negativity.

Our experiment sets this new technique as a viable method to deterministically generate highly non-classical photonic resources, lifting several major roadblocks in optical quantum engineering.

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B.15 Second-scale rotational coherence in a gas of ultracold polar molecules

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Ultracold polar molecules are emerging as a powerful platform for quantum simulation, quantum computation, precision measurement, and ultracold chemistry experiments. The rich internal structure of molecules yields a large Hilbert space in which quantum information can be encoded, while long-range and anisotropic dipole-dipole interactions can be engineered between molecules occupying quantum states in the electronic ground state where spontaneous decay is negligible.

Novel quantum computing and quantum simulation architectures are realised using arrays of optically trapped molecules. Gate operations and simulations of cold matter models can be performed utilising the resonant dipole-dipole interactions that exist between pairs of molecules prepared in different rotational energy states.

The time scale for such gate operations and simulations vary inversely with the magnitude of the strength of the dipole-dipole interactions. Achievable spacing in tweezer arrays of 1um and typical gate times tend to be on the order of milliseconds. During this time, coupled rotational states involved in the interaction must remain coherent to achieve high gate fidelity.

To achieve long coherence times, we identify a "magic" trapping frequency close to a weakly -allowed X $\rightarrow$ b electronic transition for ^{133}Rb^{87}Cs. Between the two lowest energy vibrational transitions of this excited state potential, we find a region where the anisotropic polarizability is zero for the relevant rotational energy states. This eliminates the differential AC stark shift that usually limits rotational coherence times in similar experiments.

We have recently tested the efficacy of the magic trap by performing Ramsey interferometry experiments between different rotational energy levels. We report second-scale coherence times and the observation of dipole-dipole interactions in our molecular gas. These results lay the groundwork for future experimental developments in utilising ^{133}Rb^{87}Cs as a platform for quantum technologies.

Ref.: New J. Phys. 22 013027 (2020); Phys. Rev. A 102, 053316 (2020); Phys. Rev. A 103, 043311 (2021)

B.16 Correlated insulator and supersolid phases in a one-dimensional Z_2 lattice gauge theory

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We study hard core bosons on a one dimensional lattice coupled to a dynamical Z_2 gauge field on the lattice links. Our model Hamiltonian commutes with a local Z_2 operator defined on each site. Each choice of the eigenvalue (± 1) of these local operators corresponds to a different sector of the Hilbert space. This model has been extensively studied when all eigenvalues are fixed at $+1$ and it was found that in the ground state, the bosons get confined into dimers that form a luttinger liquid at all fractional fillings without ever forming a Mott insulator state. In contrast, we consider different ordered patterns of the eigenvalues of these local operators. We find that in these sectors, the ground state can stabilize correlated mott insulator and supersolid phases at different filling fractions. We use numerical and analytical calculations to characterize the single particle spectrum and the expected many-body phases as we change the pattern of eigenvalues of the local symmetry operators. We are motivated by the recent progress in ultracold atomic experiments that can potentially realize lattice gauge theory models and observe these phases of matter.

B.17 Molecular photoionization time delays. A full-dimensional study

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The observation of electronic motion become possible after the realization of the first attosecond pulses (1 as $= 10^{-18}$ s) [1]. Therefore, it is nowadays possible to obtain time-resolved images of the formation and breaking of chemical bonds or to quantify the electron dynamics upon excitation or ionization [2]. In a photoionization event, the electron is ejected from an atom or a molecule after the interaction with an electromagnetic field. However, the emission is not instantaneous. The time the electron wave packet requires to escape is defined as photoionization time delay. The most successful experimental strategies to extract these photoionization time delays in atoms are the attosecond electron streaking [3] and the RABBITT technique [4]. Both techniques use a pump-probe scheme, combining attosecond pulses with IR fields, to characterize the electronic wave packet. The former uses a single pulse as a pump, while the latter uses a train of pulses. Scarce works have been performed in molecules [5] to date and a solid theoretical ground to understand the physical meaning of a photoionization time delay when the electron is coupled to the nuclear degrees of freedom is still to be developed. We employ as benchmark system the simplest molecule, the hydrogen molecular ion. The dependencies with the nuclear degrees of freedom are investigated by performing, for the first time, full dimensional simulations to extract molecular photoionization time delays using the above-mentioned techniques and different molecule-laser relative orientations. Comparison with (semiclassical Trajectory Monte-Carlo simulations [6] allows to disentangle distinct classical and quantum contributions to the resulting streaking time delay.

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B.18 Dynamical phases in an atom-cavity system

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We are experimentally exploring the non-equilibrium physics of a strongly coupled atom-cavity system pumped with a transversal standing wave light field. The unique feature of our system, is the small field decay rate of the cavity, which is comparable to the recoil frequency of the atoms. As a consequence of the recoil resolution, the cavity-mediated infinite-range interaction acquires a relevant degree of retardation, which leads to a qualitatively unique dynamical character. In this system, we observe a dynamical phase transition from a homogenous BEC to a self-organised superradiant phase [1]. Periodically modulating the pump strength, a new dynamical many-body phase emerges, which breaks spontaneously a discrete time-translation symmetry in an open system, dubbed dissipative time crystal [2]. For pump light blue-detuned with respect to the atomic resonance, we observed a limit cycles phase, which is characterised by periodic oscillations of the intracavity photon number, while the atomic density cycling through recurring pattern. Since the system is pumped time independent the time phase of the oscillations can take any value between 0 and 2π, as expected for a spontaneously broken continuous symmetry.

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B.19 Characterizing Operator Growth in Disordered Quantum Spin Chains via Out-of-Time-Ordered Correlators

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We investigate operator growth and information propagation in disordered, isolated quantum spin systems using out-of-time-order correlators (OTOCs) as a diagnostic tool. Specifically, we characterize the evolution of OTOCs of two initially local Pauli operators in one-dimensional XXZ Heisenberg models using numerically exact techniques. We survey both the ordered case and the disordered cases, where disorder may take the form of either random on-site potentials or random couplings from which in the limit of strong disorder many-body localization (MBL) emerges. While in ordered spin chains, operator growth is almost indistinguishable for power-law ($\alpha \geq 3$) and nearest-neighbour interactions, we observe a much faster growth in power-law interacting systems with strong on-site disorder than in their nearest-neighbour interacting counterparts. The light cones observed in the case of power-law interactions are found to be power-law, rather than logarithmic. Additionally, we propose an experimental method for measuring OTOCs with Rydberg-excited atoms through an echo scheme and analyze advantages and disadvantages of different classes of initial states to optimize measurement.

B.20 The Quantum Wigner-Smith Operator: Micromanipulation, Metrology and Vacuum Forces

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We introduce the quantum Wigner-Smith (QWS) operator, a Hermitian operator describing the interaction between the spatial as well as the quantum degrees of freedom of light and a local classical parameter of a linear, but otherwise arbitrarily complex scattering medium through which the light propagates. The QWS operator builds a bridge between quantum micromanipulation, vacuum forces and quantum metrology on the one side, and the formalism of classical scattering matrices, which are experimentally measurable in a noninvasive manner, on the other side.

The QWS operator can be used to describe generalized forces (momentum transfer, angular momentum transfer, pressure) that quantum light exerts on classical target objects. From the classical far-field scattering matrix and its dependence on the corresponding local parameter, the effect of quantum light in the near-field (in the vicinity of the target object) can be inferred. Our formalism makes it possible to identify quantum mechanical states of light that have an optimal effect (largest or smallest possible force, least possible quantum noise in the force) on the target object. If the light field is in the vacuum state, the formalism naturally provides the vacuum contributions to the forces, also known as Casimir forces.

Another application of the QWS operator lies in quantum metrology. The variance of the QWS operator is proportional to the quantum Fisher information (QFI), which in turn provides information on how precisely a

parameter of the scattering system (e.g. the position of a scatterer or its orientation) can be measured. The optimization of the QFI determines — even in complex, open scattering systems — how the spatial structure and the quantum degrees of freedom of the light must be designed in order to achieve the physically best possible measurement precision.

B.21 Optimal control of Bose-Einstein condensates in an optical lattice

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In the last twenty years, ultracold atoms trapped in optical lattices have been shown to be a well-suited platform for quantum simulations, through for instance the development of methods to produce synthetic Hamiltonians. Performing quantum simulations also requires to reliably prepare the initial state for the simulation.

I will present recent results related to the engineering of the dynamics of Bose-Einstein condensates in a one-dimensional optical lattice using quantum optimal control in order to tailor their motional state in the lattice. I will also discuss the state reconstruction method we implemented to certify the preparation of the non-trivial states obtained. I will finally illustrate the use of our optimal control method with a practical application in the field of quantum simulations.

B.22 Noisy qudits vs qubits : Conditions on Gate Efficiency

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Quantum computing faces the challenge of increasing computational capacity by scaling the number of qubits, leading to an exploration of alternative information storage and processing methods using qudits—quantum units with more than two levels. However, these extra levels may create additional pathways vulnerable to error. This study investigates the competitiveness of qudits and qubits in handling environmental errors by comparing their performance in similar conditions and using analytical formulae to assess the linear response of a multiqudit system to noise. The Average Gate Infidelity (AGI) was calculated in both systems using the Lindblad formalism, and a critical curve $O(d^2/log_2(d))$ was derived, indicating the time-efficiency of operations on these systems.

The study considered various platforms, including superconducting qubits, Rydberg atoms, trapped ions, molecular nuclear spins, and photonic qudits. The critical curve delineates regions where each system has a higher rate of increase in AGI than the other, providing a benchmark for designing future experimental implementations. Numerical simulations complemented this work, allowing for an examination of the applicability and limits of the linear response formalism.

Results suggest that qudits could still be a promising option for Quantum Information Processing (QIP), particularly when paired with specialized error correction methods. Some qudit platforms demonstrated gate efficiencies competitive with state-of-the-art qubit platforms, indicating their potential for future quantum computing advancements. Our findings can also serve as a benchmark for future experimental implementations of qudit-based quantum computing.

B.23 Tweezers arrays of erbium atoms for quantum simulation

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Quantum simulation is one of the most promising avenues of research in quantum physics, as it offers an efficient way to solve relevant quantum problems and study complex systems. To fully unlock the potential of quantum simulation, an ideal platform would need a large set of fully controllable degrees of freedom and tunable interactions. Lanthanide atoms provide such a space thanks to their large angular momentum, which can be controlled via a variety of optical transitions with laser light, together with the tunable interactions provided by excitation to Rydberg states. Moreover, the possibility of trapping single atoms in arrays of optical tweezers offers a promising gateway for upscaling, another requirement for simulating increasingly complex systems. We present here our recent progress on the implementation of a quantum simulator based on Rydberg states of erbium trapped in optical tweezers. We started by exploring several pathways to hundreds of Rydberg states, some of them originating from the 12 valence electrons in the partially filled 4f-shell characteristic of this species. We then loaded atoms in their ground state in an array of tightly focused dipole traps. From here, we plan to reach a large range of trappable Rydberg states thanks to their positive polarizability. We will then make use of the large sets of excited sub-states for demonstrating key elements necessary for quantum simulation.

B.24 Scalable spin squeezing in a dipolar Rydberg atom array

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Quantum metrology relies on the use of non-classical states of quantum many-body systems to enhance the precision of measurements beyond the standard quantum limit. In atomic systems, spin-squeezed states have been generated for metrological purposes in all-to-all coupled systems, such as trapped ions and ultracold gases [1]. Recent theoretical work has proposed that short-range interacting systems can also generate scalable spin squeezing. We present the experimental generation of spin-squeezed states in a short-range interacting system, namely two-dimensional arrays of up to $N = 100$ single Rydberg atoms interacting under the dipolar XY Hamiltonian [2]. Starting from a coherent spin state along y, the evolution of the system under the dipolar XY Hamiltonian leads to the transient formation of spin-squeezed states. We study how the amount of squeezing and the optimal squeezing time vary with the number of particles, confirming that the dipolar XY model can generate scalable spin squeezing. To enhance the metrological usefulness of these states, we demonstrate two ways to use microwave pulses to extend the time span during which the system exhibits squeezing. These results

show that scalable spin squeezing can be produced in the absence of all-to-all couplings, further demonstrating the potential of dipolar systems such as Rydberg atoms or ultra-cold molecules for quantum metrology. We also present progress on the design and construction of the next generation of our Rydberg quantum simulator.

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B.25 On-demand control of g(2) correlations of photon emission using interfering modes in collectively interacting emitters

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By using two interfering beams of light that can address different eigenmodes of the system, we can constructively or destructively control the two-excitation probabilities and hence control the emission photon statistics. The orthogonality of the eigenmodes will ensure that the $g^{(2)}$ can go from bunched to antibunched without changing the intensity of the emitted light. This can be used for having clean single photon sources or as an interesting building block for other novel applications. We also study how subradiance and superradiance affect photon statistics in the low-intensity regime. We calculate how the instantaneous two-photon correlation, or the $g^{(2)}(\tau = 0)$, is quantitatively dependent on the lifetimes of the single and double excitation eigenmodes of the system.

B.26 Certification of quantumness in the prepare-and-measure scenario

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Quantum phenomena enables strong correlations between the outcomes of spatially separated measurements performed by independent observers. These correlations enable us to distinguish the classical and quantum origins of the experiments. Paradigmatic examples are Bell nonlocality and Einstein-Podolsky-Rosen (EPR) steering. Recently, a similar distinction between classical and quantum features was found in a setup closely related to quantum communication tasks, the so-called prepare-and-measure (PM) scenario [1]. This scenario can be viewed as a communication game between two parties, Alice (the sender) and Bob (the receiver), where the dimension of the classical (versus quantum) system communicated from Alice to Bob is bounded from above. We have tested the quantumness of two-dimensional systems in the PM scenario, with n preparations and m binary-outcome measurement settings, where n and m fall well into the range of 70. In the one-qubit PM scenario, a two-level system is transmitted from the sender to the receiver. In this setup, a real $n \times m$

matrix M defines the coefficients of a linear witness. We denote by $L_2(M)$ the exact value of the one-bit bound associated with matrix M. We found efficient numerical algorithm, namely the see-saw type algorithm for computing $L_2(M)$. If this bound is exceeded, we can detect both the quantumness of the prepared qubits and the quantumness (i.e. incompatibility) of the measurements.

We introduced a new constant K_D which is related to the finite detection efficiency threshold of Bob's measurements. As an application of the above algorithm we established the lower bound $1.5682 \leq K_D$ [2].

B.27 Investigation of the dipole moment of 6,11-dihydroxy-5,12-naph -thacenedione using molecular diffraction

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Diffraction experiments with organic molecules have proven nanomechanical gratings to be a useful tool in matter-wave interference. However, interactions between the molecules and the surface of the grating can greatly affect such interference measurements. In particular, permanent electric dipole moments have been found to cause significant loss of interference contrast compared to non-polar molecules. Dephasing caused by the interactions of the electrical dipoles with charges in the nanogratings has been presented as a possible explanation for this behavior. Here we investigate the polarity of 6,11-dihydroxy-5,12-naphthacenedione, which could be assumed to be polar by the lack of inversion symmetry of its chemical structure. Measurements conducted at a silicon nitride nanograting, however, show a surprisingly high interference contrast. This may suggest a reduction of the electric dipole moment, possibly attributed to proton transfer between neighboring functional groups or averaging in the thermally excited state. Alternatively, this new grating, written by neon beam lithography in silicon nitride and coated with a 5 nm layer of gold, contains less implanted charges compared to previously used gratings. To elucidate the influence of molecular dipole moments we therefore investigate the interference contrast of other polar molecules, 5,12-naphthacenequinone and 5-(4-methoxycarbonylphenyl)-10,15,20-triphenylporphyrin. This is compared to high interference contrast for non-polar 29H,31H-phthalocyanine and mesotetraphenylporphyrin.

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B.28 Dipolar XY Magnets in a Two-dimensional Rydberg Array

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We realize a two-dimensional dipolar XY model – which exhibits a continuous spin-rotational symmetry – using a programmable Rydberg quantum simulator of up to 100 atoms. We demonstrate the adiabatic preparation of correlated low-temperature states of both the XY ferromagnet and the XY antiferromagnet. In the ferromagnetic case, we characterize the presence of long-range XY order, a feature prohibited in absence of the long-range dipolar interaction. Our exploration of the many-body physics of XY interactions complements recent works utilizing the Rydberg-blockade mechanism to realize Ising-type interactions exhibiting discrete spin rotation symmetry.

B.29 QRydDemo: A 500-qubit quantum computer demonstrator using the Sr fine-structure qubit

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The QRydDemo project aims to realize a quantum computer demonstrator with 500 qubits based on arrays of trapped Sr Rydberg atoms. Akaline-earth atoms provide an outstanding platform for fast, high-fidelity qubit control and detection. Within QRydDemo, we will utilize a novel fine-structure qubit encoded in the metastable triplet state manifold of 88Sr. By utilizing the triple-magic wavelength, wherein both the qubit states as well as the Rydberg state are identically trapped, we expect to obtain coherence times on the order of 10 ms. Two-photon Raman transitions between the qubit states will allow single-qubit gate times of 100 ns while a single-photon transition enables convenient Rydberg excitation to obtain similar gate times for two-qubit operations. As a first measurement, we will measure the Rabi oscillations between our qubit states which will form the basis of our single-qubit gates. In addition to demonstrating high-fidelity single qubit gates, using Ramsey spectroscopy, we will extract the coherence time T2 in our system and identify the main constraints in our current experimental setup. Finally, I will introduce follow-up experiments planned for the immediate future.

B.30 Reconstruction of the open quantum system with multiple isolated Random Telegraph Noise sources

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We study the open quantum dynamics under the random telegraph noise produced by one or multiple sources that do not interact with each other. Classical random telegraph noise is a Markovian stochastic process but turns quantum dynamics into a non-Markovian process when coupled with the system. In this work, we describe a system by the Markovian embedding of a composite quantum system, where the effective reservoir represents a set of noise sources. We present an algorithm based on a maximum likelihood estimation approach for finding noise parameters for every source and reconstructing the dynamics of the quantum system with a given hypothetical effective reservoir dimension.

B.31 Dual-type Dual-element Atom Array for Quantum Computation and Simulation

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Quantum science promises great potential to revolutionize our current technologies. The past few years have witnessed a rapid progress on using arrays of individually trapped atoms as a programmable quantum processor. However, several predominant challenges remain, including reconfigurable individual addressability for qubit/spin operation and non-demolish selective detection, which lead to limited efficiency in implementing quantum algorithm, low experimental repetition rate, and preclude applications of many quantum error correction protocols. Here, we are building a novel architecture that sidesteps these challenges and enable experimental study on frontier topics in quantum information dynamics, with the long-term goal aiming for a fault-tolerant general-purpose quantum computer. This architecture combines an array of individually trapped ytterbium atoms and an array of rubidium atomic ensembles in a bilayer structure, with each layer has its own unique functionality and the interlayer interaction can be tuned with external electric field rapidly via Förster resonance. Spins/qubits are encoded with the electronic states of Yb atoms, while the Rb atomic ensembles perform ancillary operations on the nearby Yb atoms, including rapidly reconfigurable local qubit operation, and fast, non-demolish detection. With these newly developed techniques, this platform can implement previously inaccessible protocols on efficient generation of target quantum states, and is compatible with quantum error correction.

B.32 Spatially Dependent Light Amplification Without Inversion

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We present a theoretical method for achieving spatially dependent amplification without inversion (AWI) by exposing a double-V quantum emitter(QE) to two weak probe beams carrying orbital angular momentum.

The QE involves four energy levels that form two interlinked V subsystems, possessing a closely spaced doublet of upper energy levels. When quantum interference in spontaneous emission from the doublet occurs, the system can exhibit spatially patterned AWI, optical transparency, and light amplification with population inversion, depending on the QE's initial state. Furthermore, we explore a scenario in which the QE is positioned in proximity to a plasmonic nanostructure and demonstrate that the degree of AWI can be controlled by adjusting the metasurface-emitter separation. This scenario allows us to achieve precise control over light-matter interactions at the nanoscale, and can be useful for advanced quantum photonic devices.

B.33 Rise and fall, and slow rise again, of operator entanglement under dephasing

D. Wellnitz, Guillermo Javier Preisser Beltrán[1], V. Alba, J. Dubail, J. Schachenmayer

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The operator space entanglement entropy, or simply "operator entanglement" (OE), is an indicator of the complexity of quantum operators and of their approximability by Matrix Product Operators (MPO). We study the OE of the density matrix of 1D many-body models undergoing dissipative evolution. It is expected that, after an initial linear growth reminiscent of unitary quench dynamics, the OE should be suppressed by dissipative processes as the system evolves to a simple stationary state. Surprisingly, we find that this scenario breaks down for one of the most fundamental dissipative mechanisms: dephasing. Under dephasing, after the initial "rise and fall" the OE can rise again, increasing logarithmically at long times. Using a combination of MPO simulations for chains of infinite length and analytical arguments valid for strong dephasing, we demonstrate that this growth is inherent to a U(1) conservation law. We argue that in an XXZ spin-model the OE grows universally as $\frac{1}{4}\log_2 t$ at long times. We trace this behavior back to anomalous classical diffusion processes.

B.34 Towards long effective-time evolution of 2D fluids of light in propagating geometries

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Quantum fluids of light have begun attracting attention as platforms capable to simulate several physical systems, whether classical or quantum. In particular, the propagation of a laser beam through a non-linear medium is formally analogous to the temporal evolution of a 2D quantum fluid. This similarity allows for a direct mapping between time in the quantum system and the beam propagation distance. Our medium of choice is hot Rb vapours due to the high flexibility in tuning the non-linearities. Despite the considerable success in simulating a large variety of physical scenarios, the study of some phenomena requires propagation distances longer than the medium (Rb cell) lenghts commonly available. Here, we propose a configuration that allows to access long effective times. Both phase and intensity of the laser field at the output of the Rb cell are carefully measured. Subsequently, by means of a spatial light modulator, the field is imaged back at the cell entrance, thus effectively achieving a feedback mechanism. By carrying out several loops, long time scales can be directly accessed at the expense of information loss at high spatial frequencies. A natural application of such a setup

consists in the study of both classical and quantum thermalisation processes and the evolution of the system towards a steady state.

B.35 Controlled flow of excitations in a ring-shaped network of Rydberg atoms

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Highly excited Rydberg atoms are a powerful platform for quantum simulation and information processing. Here, we propose atomic ring networks to study chiral currents of Rydberg excitations. The currents are controlled by a phase pattern imprinted via a Raman scheme and can persist even in the presence of dephasing. Depending on the interplay between the Rabi coupling of Rydberg states and the dipole-dipole atom interaction, the current shows markedly different features. The excitations propagate with a velocity displaying a characteristic peak in time, reflecting the chiral nature of the current. We find that the time-averaged current in a quench behaves similar to the ground-state current. This analysis paves the way for the development of new methods to transport information in atomic networks.

Ref.: F. Perciavalle *et al.*, arXiv:2212.12490 (2022)

B.36 Exploring molecular properties using far-field matter-wave diffraction

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Light gratings are a highly versatile and powerful tool in matter-wave diffraction. In atom interferometry, laser wavelengths can be tuned close to an atomic resonance to achieve precise control over internal and external degrees of freedom. However, in high-mass molecular and cluster interference, the complex internal structure of molecules poses a challenge to this approach. Instead, optical gratings in molecular interferometry utilise high power continuous wave (cw) laser light at 532 nm [1–3] or pulsed UV lasers [4,5]. Realizing cw gratings in the UV was so far hindered by the lack of lasers with sufficient output power and fast degradation of UV optics in high vacuum.

In this study, we demonstrate single-grating diffraction of molecular matter-waves at a 266 nm cw grating. Compared to diffraction at 532 nm gratings, this results in a wider spacing of the diffraction orders, enabling the exploration of more massive molecules compared to previous far-field experiments. Our focus is on applications

for quantum-assisted measurements, using diffraction images to extract molecules' intrinsic optical properties such as polarizability and absorption cross section at 266 nm. The deep UV diffraction grating paves the way for studying photo-physical and photo-chemical processes of biologically and technologically relevant molecules in matter-wave diffraction. Furthermore, it explores new grating mechanisms for high-mass cluster interferometry and complex biomolecules, such as continuous depletion gratings based on single photon induced photocleavage.

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B.37 High-speed Interleaved SNSPDs with nanosecond scale gating option

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For applications that require high-speed and/or photon-number resolution, multipixel superconducting nanowire single-photon detectors (SNSPDs) in the telecom range are very attractive. Single Quantum developed a detector demonstrating system detection efficiency $> 80\%$ at 1550nm, with full efficiency recovery after 8 ns and 3dB efficiency-point close to 700 Mcts along with an outstanding timing detection jitter < 15 ps and Dark Count rate < 100 Hz. Such detector enables fast on-off gating at unprecedented ns time-scales becoming particularly interesting in applications where noise reduction and temporal filtering is required. Resonant fluorescence spectroscopy is one great examples

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B.38 Trapping-Arrays of interacting Circular Rydberg Atoms

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Rydberg atoms are particularly well suited for quantum simulation, thanks to their strong interactions even at a few micron distance. Regular arrays of Rydberg atoms are now being used in many experimental setups. The simulation time is limited both by the lifetime of the laser-accessible Rydberg levels – typically 100 µs – and by the fact that Rydberg atoms are not trapped during the simulation.

Circular Rydberg atoms, the natural lifetime of which reaches several 10 ms [1], offer the perspective to run quantum simulation over unprecedented timescales [2]. To leverage these long lifetimes, it is however mandatory to laser-trap circular Rydberg atoms [3].

Here, we report the successful trapping of many single circular Rydberg atoms in a holographically-shaped laser array. We also prepare independent pairs of laser-trapped circular Rydberg atoms, and characterize their dipole-dipole interaction.

Laser-cooled Rubidium atoms are initially trapped in an arbitrary array of gaussian-shape optical tweezers. Then, they are promoted to the n=52 circular Rydberg levels, while being transferred into "bottle" optical beams, that trap the circular Rydberg atoms through a ponderomotive force. We develop a novel optical detection of circular states, that is both spatially and level selective. We use it to demonstrate the laser-trapping and to study the two-body interaction.

Our results open a new route for quantum technologies with Rydberg atoms, allowing one to exploit the unique properties of the circular levels.

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B.39 Multifractality in the interacting disordered Tavis-Cummings model

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We analyze the spectral and transport properties of the interacting disordered Tavis-Cummings model at half excitation filling. We demonstrate that a poissonian level statistics coexists with eigenfunctions that are multifractal (extended, but non-ergodic) in the Hilbert space, for all strengths of light-matter interactions. This is associated with a lack of thermalization for a local perturbation, which remains partially localized in the infinite-time limit. We argue that these effects are due to the combination of finite interactions and integrability of the model. When a small integrability-breaking perturbation (nearest-neighbour hopping) is introduced, typical eigenfunctions become ergodic, seemingly turning the system into a near-perfect conductor, contrary to the single-excitation non-interacting case. We propose a realization of this model with cold atoms.

B.40 Towards the control of temporal entangled single-photon pulses in the presence of magnetic field

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Quantum entanglement is one of the most fascinating phenomena in modern physics and it has emerged as a powerful resource for quantum information processing and communication. Time-bin entanglement, where two photons are entangled on their arrival times, is a particularly important form of entanglement for several applications, such as quantum key distribution and quantum teleportation, since they are robust against noises, enabling long distance communication. Several schemes have been proposed to generate single-photon time-bin entangled qubits that require precise control of the system parameters. Currently we propose a new method to control time-bin entangled states in tripod atoms driven by an external magnetic field. The presence of magnetic field changes strongly atomic transition probabilities, allowing different group velocities produced at the different transitions of tripod atoms. This, in turn, leads to a comparably easy control of time-bin entanglement. The effect is theoretically shown, considering cold ensemble of $^{Rb}87$ atoms, $F = 1 \rightarrow F' = 0$ transition. The single photons are in resonance with the σ^+ and σ^- transitions, while a laser field of π polarisation provides electromagnetically induced transparency conditions for the single-photon pulses. By changing the value of external magnetic field from 0 to 20 G, we can reach a ratio of ten between the relative group velocities of the two entangling bins. At the same time, even a field amplitude as low as 2 G is sufficient to reach few MHz of frequency shift between the ground states Zeeman sublevels, which allows excitation of specific atomic states.

B.41 FermiQP - A Fermion Quantum Processor

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FermiQP is a demonstrator for a neutral atom quantum processor based on ultracold fermionic lithium in optical lattices. In its digital mode, it will serve as a fully programmable quantum computer with single-qubit gates implemented as Raman rotations between hyperfine states and two-qubit gates realized via controlled collisions in two-dimensional superlattices. Tweezer-based resorting techniques will enable entangling operations across the entire lattice. In the analog mode, the experiment will operate as a quantum simulator for the Fermi-Hubbard model with additional control over the starting configuration. Building on previously developed techniques, the microscope will feature imaging and addressing at the single-atom level as well as spin-resolved state detection. We are building the experiment using a single-chamber design with the goal to reduce cycle times. The compact vacuum chamber allows for easier maintenance and increases flexibility. On the poster, we present the most recent developments on the experiment.

B.42 A cryogenic neutral atom optical tweezer array

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Scalable ultracold Rydberg atom arrays provide an intriguing platform for programmable quantum computation. We present a new system for the control of 2D Rydberg qubit arrays of ^{87}Rb atoms embedded in a cryogenic environment. The setup leverages two main features: a low-vibration cryostat and a high optical access vacuum chamber. Compared to conventional room-temperature setups, cryopumping improves the atom vacuum lifetime to fully leverage the scalability of Rydberg platforms, and a 30 K environment extend the Rydberg lifetime to several times its value at room temperature. The high-optical access vacuum chamber will allow the creation and control of a large array using a 2D optical lattice with the site-resolved addressability and interaction control aided by optical tweezers. We will harness a bi-chromatic magic lattice to provide identical confinement for both ground and Rydberg states. We report our results on trapping atoms within the cryogenic environment, as well as preliminary results on qubit control.

B.43 Rydberg quantum simulator using strontium atoms in tweezers

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We demonstrate the preparation of defect-free patterns of single Sr atoms in optical tweezers. The Sr atoms form the qubit register of our programmable Rydberg quantum simulator. This platform is highly suitable to study for example large scale spin-1/2 systems. The qubit states are encoded onto two electronic levels of the atoms. The qubits are selectively read-out using fluorescence imaging on the narrow $^1S_0 - ^3P_1$ transition with 99.9% fidelity and survive imaging exposure up to 78 s. As a first step towards quantum simulation, we show coherent excitation of n=61 $^3S_1$ Rydberg states in our array, for single atoms and for blockading pairs. We further present an outlook for implementing a universal gate set for quantum computing using this system similar to the recent work [1]. This research is part of the KAT-1 quantum computing demonstrator programme of Quantum Delta NL.

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B.44 Optimized tomography of a complex collective quantum state

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Quantum-information applications rely on accurate reconstruction of quantum states. The reconstruction reliability is crucial for quantum algorithms, but is challenging due to the strength of signals originating from single quantum objects (e.g., atoms, ions, and photons), that are often used for information storage. To alleviate this problem, collective quantum states generated in systems consisting of a macroscopic number of such microscopic objects can be used. The solution not only offers better accuracy in state reconstruction, but also enables the implementation of means of quantum nondemolition measurements.

We present a novel optical technique for measuring a collective quantum state in room-temperature rubidium vapor. By detecting properties of light traversing the vapor, we can perform full reconstruction of a state consisting of three long-lived (>10 ms) energy levels. As the quantum state of the system can be manipulated with both light and magnetic fields, this system serves as a practical implementation of a qutrit, a three-dimensional quantum-information unit.

To optimize the reconstruction process, we conducted a theoretical study using so-called conditional numbers. These numbers determine the robustness of the implemented reconstruction procedure against noise and experimental uncertainties. Using the optimized technique, we reconstruct several different quantum states generated in the vapor.

This study is the first stage of our attempt to reconstruct the quantum state of all ground-state sublevels of alkali-metal atoms. If successful, the technique has the potential to advance quantum-information applications and enable the development of more robust and reliable quantum-information algorithms.

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C Fundamental physics

C.1 Three interacting particles in a circular trap: periodic trajectories and bifurcations

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Experiments involving chains of Rydberg atoms [1] have led to the observation of many-body scarring [2], which is an ergodicity-breaking mechanism related to quantum scars [3]. We have recently proposed [4] a system of three interacting particles in a circular trap, and identified unstable classical periodic trajectories yielding a series of quantum scars due to the interparticle interaction, which may be realised using Rydberg atoms. In the present work, we characterise the mixed phase space of this system, and systematically explore its stable and unstable classical periodic trajectories and bifurcations, highlighting the role of discrete symmetries.

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C.2 Interference dynamics of matter-waves of SU(N) fermions

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We analyze the two main physical observables related to the momenta of strongly correlated SU(N) fermions in ring-shaped lattices pierced by an effective magnetic flux: homodyne (momentum distribution) and self-heterodyne interference patterns. We demonstrate how their analysis allows us to monitor the persistent current pattern. We find that both homodyne and self-heterodyne interference display a specific dependence on the structure of the Fermi distribution and particles' correlations. For homodyne protocols, the momentum distribution is affected by the particle statistics in two distinctive ways. The first effect is a purely statistical one: at zero interactions, the characteristic hole in the momentum distribution around the momentum k = 0 opens up once half of the SU(N) Fermi sphere is displaced. The second effect originates from interaction: the fractionalization in the interacting system manifests itself by an additional "delay" in the flux for the occurrence of the hole, that now becomes a depression at $k = 0$. In the case of self-heterodyne interference patterns, we are not only able to monitor, but also observe the fractionalization. Indeed, the fractionalized angular momenta, due to level crossings in the system, are reflected in dislocations present in interferograms. Our analysis demonstrates how the study of the interference fringes grants us access to both number of particles and number of components of SU(N) fermions.

C.3 Spectral Properties of Quantum Graphs and Microwave Networks

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Quantum graphs i.e. network of bonds connected at vertices, provides more efficient model systems for the experimental and theoretical study of a closed and open quantum system with chaotic classical dynamics. The models of quantum graphs were widely used to investigate many physical systems, e.g., quantum wires, mesoscopic quantum systems, a topological edge invariant, and the photon number statistics of coherent light. In the current study, we show that there is a relationship between the generalized Euler characteristic εo(|VDo|) of the original graph that was split at vertices or edges into two disconnected subgraphs $i = 1, 2$ and their generalized Euler characteristics εi(|VDi|). Here, |VDo| and |VDi| denote the numbers of vertices with the

Dirichlet boundary conditions in the graphs. We demonstrated that the evaluation of the generalized Euler characteristics $\varepsilon o(|VDo|)$ and $\varepsilon i(|VDi|)$ allows us to determine the number of vertices or edges where the two subgraphs were initially connected.

C.4 Zeeman-Sisyphus Deceleration of CaF

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Compared to atoms, the more complex internal structure of molecules opens up exciting possibilities for quantum simulation and tests of fundamental physics, but also presents experimental challenges. For instance, the capture velocity of molecular MOTs is only around 20m/s and this places even greater importance on the use of slowing techniques for effective MOT loading. While direct laser slowing can be applied to a limited subset of molecules, scattering the 10^4 photons required to bring molecular beams at 70-200m/s to rest is impractical for other molecular species. This includes those with unfavourable branching ratios which will be quickly lost from the cycle without repumping, and heavier polyatomic species which require even more scattering events. The finite transverse velocities of molecules leaving the source also limits the number which can be loaded into the MOT, with many lost as the beam diverges. Zeeman-Sisyphus deceleration presents a novel way to address these concerns, reducing the number of photon scatters required by at least two orders of magnitude compared to laser slowing. Molecules travel through a spatially varying magnetic field and are optically pumped between high and low field seeking substates to ensure they are continually climbing a potential hill. The magnetic field also provides transverse guiding and has the additional benefit of being time-independent. Zeeman-Sisyphus deceleration has previously been demonstrated successfully for CaOH [1] and YbOH [2], in a two-stage decelerator made up of cryogenically cooled superconducting solenoids. Here, we present our plans to build upon this work, experimentally realising the Zeeman-Sisyphus decelerator outlined in [3] for CaF, which uses permanent magnets and will be extendable to hundreds of deceleration stages.

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C.5 Relative dynamics of quantum vortices and massive cores in binary BECs

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We study vortices with massive cores [1,2] in binary mixtures of Bose-Einstein condensates. We consider the case of a simple 2D disc geometry. Taking up the work of Richaud et al. [3,4], we introduce a point-vortex model where quantum vortices in the majority species are coupled to the corresponding core masses, i. e. local peaks of the minority species. The point-like dynamics is obtained via a variational Lagrangian approach. In parallel, we validate our analytical results via the numerical resolution of two coupled Gross-Pitaevskii equations. Conversely to the previous works, where a vortex centre was assumed coincident with the centre of its massive core, we instead introduce a more refined dynamical model: here, the two objects are described by independent sets of dynamical variables and coupled by an harmonic term. Consequently, we study the effect of the new degree of freedom on the vortex-mass relative motion and average dynamics. As already observed, the first striking effect of the second species is a change of trajectory. Whereas a massless vortex in a 2D disc moves of uniform circular motion, in presence of a second species some radial oscillations may arise. Specifically, our new model brings to a more articulated normal mode analysis, and improves the previous model thanks to the dependency of the small oscillations on the inter-species coupling parameter g_{ab}. This dependency could not be appreciated in the previous model as it did not include the parameter g_{ab} at all. On the other hand, we confirm that there is no significant relative motion of the vortex with respect to its core mass.

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C.6 Towards a High-Precision Atomic Mass Measurement of the ^{3}He Nucleus at LIONTRAP

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The most precise mass measurements of light nuclei today are performed using Penning traps. Together, these measurements provide a network of essential parameters for fundamental physics. For example, the mass difference of T and ^{3}He is used as a consistency check for the model of systematics in the KATRIN experiment, which studies the endpoint of the T β-decay spectrum to set a limit on the $m(\bar{\nu}_e)$ mass [1].

Recently performed high-precision mass measurements of the lightest nuclei, including ^{3}He, have revealed considerable inconsistencies between tabulated values reported by different world-leading experiments. This discrepancy is known as the "light ion mass puzzle". In order to provide an independent cross-check, the multi-Penning-trap mass spectrometer LIONTRAP has obtained the masses of the proton [3], the deuteron and the HD^+ molecular ion, which are consistent with the results of FSU and the values extracted from laser spectroscopy of HD^+ [4].

At present, activities of the experiment are directed at the atomic mass measurement of the ^{3}He nucleus with a relative uncertainty lower than 10 parts-per-trillion. This contribution presents the status of the ongoing mass measurement campaign.

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C.7 On-demand control of g(2) correlations of photon emission using interfering modes in collectively interacting emitters

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By using two interfering beams of light that can address different eigenmodes of the system, we can constructively or destructively control the two-excitation probabilities and hence control the emission photon statistics. The orthogonality of the eigenmodes will ensure that the $g^{(2)}$ can go from bunched to antibunched without changing the intensity of the emitted light. This can be used for having clean single photon sources or as an interesting building block for other novel applications. We also study how subradiance and superradiance affect photon statistics in the low-intensity regime. We calculate how the instantaneous two-photon correlation, or the $g^{(2)}(\tau = 0)$, is quantitatively dependent on the lifetimes of the single and double excitation eigenmodes of the system.

C.8 ALPHATRAP: High-precision single-ion measurements in a Penning Trap

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The ALPHATRAP experiment is a double Penning-trap setup at the Max Planck Institute for Nuclear Physics in Heidelberg. The cryogenic trap setup allows for high-precision spectroscopic measurements on single ions by utilizing the continuous Stern-Gerlach effect for non-destructive spin-state detection. It is connected by a room-temperature beamline to several different ion sources which can produce a wide range of charge states for a broad range of measurements.
In this contribution, recent and ongoing measurement campaigns are presented. This includes a brief overview

over the spectroscopy of electron g factors in the HD^+ molecular ion. Furthermore, our recent measurement of the bound-electron g factor in hydrogenlike tin will be presented. Its comparison with the theoretical prediction allows a stringent test of bound-state QED in the strong electric fields the electron perceives from the high-Z nucleus.

C.9 Resonant X-ray scattering by highly-charged ions exposed to magnetic fields

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The interaction of X-rays with highly charged ions is an important tool to study and characterize many astrophysical plasmas. The processes of high-energy light-ion interactions can also be studied under laboratory conditions, by employing electron beam ion traps (EBIT) and synchrotron radiation. Recently, for example, the elastic resonant scattering of linearly polarized X-rays by helium-like nitrogen ions was measured at the Elettra synchrotron radiation facility in Trieste using the portable PolarX-EBIT. In this experiment, one observed $1s^2\,{}^1S_0 + \gamma \to 1snp\,{}^1P_1 \to 1s^2\,{}^1S_0 + \gamma$ transitions for various excited states with $n = 2, \cdots, 7$, and paid special attention to the probabilities of the photon scattering either in parallel ($W_\parallel$) or perpendicular ($W_\perp$) direction to the linear polarization vector of the incident radiation. It was shown, in particular, that the ratio is highly sensitive to the principal quantum number n of an ionic state $1snp\,{}^1P_1$ through which the resonant scattering occurs. In order to explain this n-dependence, we present a theoretical study of the x-ray elastic scattering by ions, exposed to a magnetic field of an EBIT. We demonstrate that the B-induced Zeeman splitting of the magnetic sublevels of $1snp\,{}^1P_1$ states may drastically affect the angular distribution of scattered photons, very similar to the well-known Hanle effect. Moreover, a simple analytical expression for the ratio $W_\parallel/W_\perp$ is derived, whose predictions explain well the experimental results.

C.10 Polarization Phenomena of Photonic Processes in the Hard X-Ray Regime Revealed by Compton Polarimetry

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For photon energies from several 10 keV up to a few MeV, Compton polarimetry is an indispensable tool to gain insight into subtle details of fundamental atomic radiative processes. Within the SPARC collaboration [1] several segmented semiconductor detectors are developed that are well suited for application as efficient Compton polarimeters. Such Compton polarimeters enable to reveal in great detail photon polarization effects for electron-photon and photon-photon scattering processes in the hard x-ray regime and to test underlying fundamental theories. Particular emphasis is given to processes common in astrophysical objects or more general for processes in the hard x-ray regime such as radiative recombination, electron bremsstrahlung, Rayleigh and Compton scattering where spin-effects and polarization transfer phenomena are of great importance. Based on a dedicated Compton telescope, these studies will be extended in the near future to recombination studies for polarized electrons and to Delbrück scattering. In our presentation, an overview on our current experimental projects will be presented.

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C.11 Theoretical study of spin polarization in multiphoton ionization of Xe

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Spin polarization in the multiphoton above-threshold ionization of 5p3/2 - and 5p1/2 -electrons of Xe with intense 395 nm circularly polarized laser pulses is investigated theoretically. To this end, we include the spin-orbit interaction explicitly into the Hamiltonian and solve the time-dependent Schrödinger equation using the basis of spherical spinors. We, thus, simultaneously propagate the spin-up and spin-down single-active-electron wave packets, driven by the laser pulses in the ionic potential in presence of the spin-orbit interaction. The present theoretical results agree well with the recent experimental results [1].

This work presents the extension of the time-dependent single-center (TDSC) method [2] toward describing spin-polarization effects. Previously (see e.g. [3] and references therein) TDSC method has been successfully applied to the angular-resolved calculations of the photoelectron spectra and photoelectron circular dichroism in the ionization of chiral molecules by the circularly polarized intense laser field in various ionization regimes.

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C.12 Full relativistic electronic structure calculations of TlCl for laser cooling experiment

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Following the interest in the experimental realization of laser cooling for thallium fluoride (TlF), determining the potential of thallium chloride (TlCl) as a candidate for laser cooling experiments has recently received attention from a theoretical perspective. From these ab initio electronic structure calculations, it appeared that the cooling process, which would proceed from transitions between a3Π+0 and X1Σ+0 states, had as a potential bottleneck the long lifetime (6.04 μs) of the excited state a3Π+0, that would make it very difficult to experimentally control the slowing zone.

In this work, we revisit the electronic structure of TlCl by employing four-component Multireference Configuration Interaction (MRCI) and Polarization Propagator (PP) calculations and investigate the effect of such approaches on the computed transition dipole moments between a3Π+0 and a3Π1 excited states of TlCl and TlF (the latter serving as a benchmark between theory and experiment). Whenever possible, MRCI and PP results have been cross-validated by four-component equation of motion coupled-cluster calculations. We find from these different correlated approaches that a coherent picture emerges in which the results of TlF are extremely close to the experimental values, whereas for TlCl the four-component calculations now predict a significantly shorter lifetime (between 109 and 175 ns) for the a3Π+0 than prior estimates. As a consequence, TlCl would exhibit rather different, more favorable cooling dynamics. By numerically calculating the rate equation, we provide evidence that TlCl may have similar cooling capabilities to TlF.

C.13 Lifetimes of excited states of the lanthanum negative ion

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Negative ions are interesting both for their importance in a variety of physical processes and for the essential insights they can provide into electron correlations. Because the extra electron in a negative ion is not bound to the neutral core by a net Coulomb force, stability depends crucially on electron interactions. The shallow potential well in an atomic negative ion typically supports only a single bound state configuration. To date, electric dipole (E1) allowed transitions between bound states have been directly observed in only four atomic negative ions. Among these, the negative ion of lanthanum is particularly intriguing because of its large number of bound states of both even- and odd-parity. The E1 transition between the La- 3F2e ground state and 3D1o excited state has been proposed as a promising candidate for laser cooling due to its relative strength and nearly closed channel cycle. A potential complication for laser cooling of La– is predicted leakage from the closed cycle due to decay branching of 3D1o to long-lived excited fine structure levels that may require re-pumping.

In the present work, the lifetimes of low-lying bound excited states of La– were measured at the DESIREE facility at Stockholm University. Ions were injected into the cryogenic electrostatic ion-beam ring, and the

populations of different states were monitored over storage times up to 800 s using selective photodetachment. The observed photodetached neutral atom signals as functions of time were fit with exponentials to extract the radiative decay lifetimes of the excited states. The measured lifetimes for the predominantly magnetic dipole decay of the excited fine structure levels will be compared to previous theoretical predictions of the lifetimes of ~ 130 s. These results give further insights into the structure and dynamics of La– that will help assess its feasibility for laser cooling applications.

C.14 Extension of Judd-Ofelt theory: Application on trivalent Eu, Nd and Er

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We present a modified version of the Judd-Ofelt theory, which describes the intensities of f-f transitions for trivalent lanthanide ions (Ln^{3+}) in solids. In our model, the properties of the dopant are calculated with well-established atomic-structure techniques, while the influence of the crystal-field potential is described as a perturbation, by three adjustable parameters. Compared to our previous work [1], the spin-orbit interaction within the fist excited configuration $4f^{n-1}5d$ is described in a perturbative way, whereas it is exactly taken into account in the ground configuration $4f^n$, using all the eigenvector components of the free-ion levels. Moreover, using the Sellmeier equation, the wavelength-dependence of the refractive index of the host material is also accounted for. We test the validity of our model on three ions: Eu^{3+}, Nd^{3+} and Er^{3+}. The results of the extension are satisfactory, we are able to give a physical insight into all the transitions within the ground electronic configuration, and also to reproduce quantitatively experimental absorption oscillator strengths. We also performed calculations of standard JO parameters, and the results are in good agreement with the values reported in the literature.

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C.15 Molecular-frame photoelectron circular dichroism of O 1s-photoelectrons of trifluoromethyloxirane

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The photoelectron circular dichroism (PECD) [1] manifests itself as a substantial laboratory-frame forward-backward asymmetry in the emission of photoelectrons with respect to the propagation direction of circularly polarized light. Usually PECD studies are performed for randomly oriented molecules in the gas phase, and this chiral asymmetry reaches a few percent of a total cross section. One of the methods to increase the size of this effect is to fix a chiral molecule in space [2]. As it was shown in References [2, 3], fixing one molecular-orientation axis in space can enhance a PECD up to about 20%. In this work, we study experimentally and theoretically the PECD of the fully fixed in space trifluoromethyloxirane (TFMOx) molecule, as a function of the two photoelectron emission angles. The experimental data for the O 1s photoionization of R-TFMOx [4] were recorded at Synchrotron SOLEIL (Saint-Aubin, France) at beamline SEXTANTS using cold target recoil ion momentum spectroscopy for 5 photoelectron kinetic energies. Theoretical ab initio calculations were performed by the single center method [5]. The value of the computed differential PECDs exceeds 80%, whereas the measured one is somewhat smaller and reaches 50%. Our studies confirm that orienting the molecule increases the dichroic contrast of this chiral asymmetry by up to two orders of magnitude, which significantly enhances its sensitivity for chiral recognition in the gas-phase.

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C.16 The most condense material in the Universe; 10^{25} times of a black hole (Cidtonium)

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If we want to get the constituent of the Big Bang, we can suggest the photon as the option which based on Saleh Theory is particle. Accordingly the volume and density of the Big Bang will be: $m_T = 10^{53}\ kg$
$m_p = 1.67 \times 10^{-35}\ kg$
$r_p = 1.2 \times 10^{-17}\ m$
$n = \frac{m_T}{m_p} = \frac{10^{53}}{1.67\times10^{-35}} \Rightarrow n = 6 \times 10^{87}$
$V_p = \frac{4}{3}\pi {r_p}^3 = \frac{4}{3}\pi(1.2 \times 10^{-17})^3 \Rightarrow V_p = 7.23 \times 10^{-51}\ \ m^3$

$\rho_p = \frac{m_p}{V_p} = \frac{1.67\times10^{-35}}{7.23\times10^{-51}} \Rightarrow \rho_p = 2.31\times10^{15}\ \frac{kg}{m^3}$
$V_{BB} = nV_p = 6\times10^{87}\times7.23\times10^{-51} \Rightarrow V_{BB} = 4.33\times10^{37}\ m^3$
$V_{BB} = \frac{4}{3}\pi {r_{BB}}^3 \Rightarrow {r_{BB}}^3 = \frac{4.33\times10^{37}}{\frac{4}{3}\pi} \Rightarrow r_{BB} = 2.18\times10^{12}\ m$
$\rho_{BB} = \frac{m_T}{V_{BB}} = \frac{10^{53}}{4.33\times10^{37}} \Rightarrow \rho_{BB} = 2.31\times10^{15}\frac{kg}{m^3}$ Where m_T is the total mass of universe, n is the number of photon, m_p, r_p, V_p and ρ_p are the mass, radius, volume and density of the photon and r_{BB}, V_{BB} and ρ_{BB} are the radius, volume and density of the Big Bang sphere. Considering that the density of the Big Bang obtained by using photons is about $10^{15}\ \frac{kg}{m^3}$ and as instant, the radius of the Big Bang sphere will be from the Earth to Jupiter. So, it could not be a suitable choice for the Big Bang, because it does not meet the definition that we expect for the Big Bang. In order to achieve our desired goal, we define a particle whose radius is one billionth of a photon, "Cidtonium". According to this new particle we have: $r_C = r_p\times10^{-9} = 1.2\times10^{-26}\ \ m$
$V_C = \frac{4}{3}\pi {r_C}^3 = \frac{4}{3}\pi(1.2\times10^{-26})^3 \Rightarrow V_C = 7.23\times10^{-78}\ \ m^3$
$\rho_C = \frac{1.67\times10^{-35}}{7.23\times10^{-78}} \Rightarrow \rho_C = 2.31\times10^{42}\ \frac{kg}{m^3}$
$\acute{V}_{BB} = nV_C = 6\times10^{87}\times7.23\times10^{-78} \rightarrow \acute{V}_{BB} = 4.33\times10^{10}\ m^3$
$\acute{V}_{BB} = \frac{4}{3}\pi \acute{r}^3_{BB} \Rightarrow \acute{r}^3_{BB} = \frac{4.33\times10^{10}}{\frac{4}{3}\pi} \Rightarrow \acute{r}_{BB} = 2.18\times10^3\ m$
$\acute{\rho}_{BB} = \frac{m_T}{\acute{V}_{BB}} = \frac{10^{53}}{4.33\times10^{10}} \Rightarrow \acute{\rho}_{BB} = 2.31\times10^{42}\ \frac{kg}{m^3}$ Where n is the number of Cidtonium, m_C, r_C, V_C and ρ_C are the mass, radius, volume and density of the Cidtonium and $\acute{r}_{BB}, \acute{V}_{BB}$ and $\acute{\rho}_{BB}$ are the radius, volume and density of the Big Bang sphere based on Cidtonium. It is clear that the size of the Big Bang sphere based on Cidtonium is about the moon and the density is about $10^{42}\ \frac{kg}{m^3}$. Therefore, this particle could be a suitable choice for the nature of the Big Bang.

C.17 A New Explanation for How Black Holes Are Created and Their Types

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Considering that our universe is about 14 billion years old and there are galaxies whose lifetime is about 13 billion years, it can be concluded that their core, black holes, was formed at the beginning of the Big Bang. In fact, initial black holes are a part of the initial Big Bang that has the ability to create black holes with a density of $10^{20}\ \frac{kg}{m^3}$. For more explanation, we note the following contents:

A. Objects whose density is between 0 to $10^6\ \frac{kg}{m^3}$. Those include all types of elements and atoms

B. Matters whose density is between 10^{14} to $10^{20}\frac{kg}{m^3}$, such as black holes, white dwarfs and magnetars.

C. Big Bang whose density is about $10^{42}\frac{kg}{m^3}$.

Accordingly, there must be matters whose density is between 10^{20} and $10^{40}\frac{kg}{m^3}$, which are lost and unknown for us. Therefore, there are separated components from the Big Bang that have the density of $10^{40}\frac{kg}{m^3}$. During the explosion of the Big Bang, all the types of different matters, including black holes, are created. In fact, the explosion of the Big Bang could create 3 types of black holes:

1. Regular black hole: black holes with an average density of $10^{20}\frac{kg}{m^3}$
2. Super black hole: black holes whose average density is about $10^{26}\frac{kg}{m^3}$, and

3. Meta black hole: black holes whose average density is about $10^{32}\,\frac{kg}{m^3}$.

For example: The Milky Way galaxy has a regular black hole at its center, the Andromeda galaxy has a super black hole at its center, and the Pleiades, whose central galaxy has a Meta black hole at its center.

C.18 A polyatomic molecular cryogenic buffer gas beam for tabletop precision experiments

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Polyatomic molecules have become important candidates for testing parity and time violating physics beyond the standard model. Polyatomic molecules allow for an improved eEDM measurement. Unlike diatomic molecules, polyatomic molecules can combine favorable characteristics like parity doublets in the ground state and heavy nuclei without in principle a loss of laser-coolability. It is the aim of this project to combine theory with experiment for a range of polyatomic molecules in order to find optimal candidates for future eEDM searches. This poster focuses on the development of a versatile cryogenic buffer gas source capable of producing a range of polyatomic molecules in an intense and slow beam.

C.19 Quadratic Zeeman effect in light three-particle systems

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The spectroscopy of light atomic and molecular systems allows for precise study of fundamental laws of physics [1,2]. For example, in recent measurements of the HD^+ ions' spectrum, the proton-to-electron mass ratio has been determined with improved accuracy [1]. In many cases, the system cannot be considered in isolation. The inclusion of interactions with the environment, such as the Stark and Zeeman effects, are key to the proper analysis of the results from precise spectroscopy experiments. Interactions of hydrogen molecular ions with magnetic fields have been studied by many authors, e.g. in [3]. However, of primary interest has been the leading Zeeman effect. But in some cases, the second order effects are important too. The quadratic Zeeman effect has leading role for very strong magnetic fields that exist for example in astrophysics. Knowing the effects of the diamagnetic interaction also becomes very important in the contemporary high precision spectroscopy experiments [1, 4]. Here, we investigate the quadratic Zeeman effect in three particle systems like H_2^+ and $\bar{p}He^+$. Accurate results for the diamagnetic interaction in these systems are obtained for a wide range of magnetic field strengths.

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C.20 High-resolution mid-infrared molecular spectroscopy with cold molecules for fundamental tests

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High precision spectroscopy of molecular systems offers fascinating perspectives in fundamental physics, from the measurement of fundamental constants or their variation in time to tests of fundamental symmetries. Ultra-precise spectroscopy has for instance been proposed to measure the tiny energy difference between enantiomers of a chiral molecule [1], a signature of electroweak-interactions-induced parity violation (PV), and a sensitive probe of dark matter. Despite being theoretically predicted, no experiment has ever reached the required sensitivity to measure this tiny energy difference. We will report our ongoing efforts towards developing a new experimental set-up dedicated to high-precision vibrational spectroscopy of cold polyatomic molecules in the gas phase, to be used in particular to test PV in organo-metallic chiral species such as rhenium [2], and ruthenium or osmium [3] complexes for which the PV energy difference between enantiomers is predicted to be measurable. We will present preliminary results on buffer-gas cooling of complex polyatomic molecules [4] and investigations of new methods combining mid-infrared and microwave fields to enhance detection sensitivity compared to conventional direct mid-infrared absorption schemes.

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C.21 Elastic scattering of twisted electron wave packets by crystals

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Electron beams carrying a well-defined orbital angular momentum (OAM) projection upon their propagation direction were firstly produced in 2010 and have been studied intensively in the past [1]. Many possible applications of such vortex beams have been proposed such as high resolution phase contrast imaging, spintronic applications and the manipulation of nanoparticles [2]. Moreover, the employment of vortex electron beams in transmission electron microscopy (TEM) also attracted particular attention during the recent years [3]. In this contribution, we present a theoretical analysis of the elastic scattering of tightly focused vortex electron beams as can be used in TEM techniques. In particular, we employ the generalized Born approximation [4,5] to investigate the scattering of a Bessel-Gaussian (vortex) wave-packet off a graphene layer. Detailed calculations, performed for 1.4 keV electrons, indicate that the scattering cross section is very sensitive to both the OAM projection of vortex electron beam as well as to its waist parameter.

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C.22 Manipulation of Impurities in a Fermi Sea with Raman Transitions

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Ultracold quantum gases with tunable interactions provide a well-controllable environment to investigate interacting many-body systems. In the case of strongly imbalanced mixtures, impurity physics in the quantum regime can be studied. Our system consists of either fermionic 40 K or bosonic 41 K impurities interacting with a Fermi sea of ^{6}Li atoms. This many-body system can be described in terms of quasiparticles named polarons. Static and dynamic properties of the polaron have been studied in previous work using radio-frequency spectroscopy [1-3]. In order to get access to kinetic properties of the polaron like the effective mass and dispersion relation, Raman spectroscopy can be used [4]. In addition to the control of the internal state, Raman transitions allow manipulation of the momentum state of the impurity. Here, we present the experimental setup together with a quantitative characterization of the Raman coupling in bosonic 41 K. The setup enables transfer of multiple momenta to the impurities and single Raman π-pulses with durations down to 36 ns.

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C.23 Influence of the saturation effect on the Zeeman and hfs spectra

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The technique of laser absorption spectroscopy is widely used in the study of the atomic structure.

However, when the atomic structure is very rich and the individual components overlap, problems arise with the correct positioning of the corresponding intensity peaks. An additional problem is the saturation effect. Standard fitting procedures take into account the theoretically predicted relative intensities of the individual components. Due to the saturation effect, the intensities of individual components differ from those predicted theoretically, and the theoretically predicted shape of the spectrum does not agree with the experimental results. Sometimes it is possible to reduce the laser power to a level where the observed intensities are as predicted, but in many cases the saturation effect cannot be avoided. Due to the saturation effect, the stronger components have relatively lower intensities compared to the weaker components.

Based on the theoretical description of the saturation effect, which can be found in the Demtröder monograph and many other publications, we present a method that allows to take this effect into account in computer simulations of the Zeeman and hfs spectra.

The most important conclusion of our studies is that measurements of hyperfine structures should be carried out in conditions where the polarization state of the exciting laser light is known, which should be reflected in simulations fitting the shape of the experimental spectrum to the theory.

C.24 Accurate molecular ab initio calculations in support of strong-field attosecond physics experiments

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Experimental techniques exploiting strong-field processes allow for investigating the attosecond dynamics of molecules, such as their fragmentation into atoms [1]. Such experiments consist of a first step, where the molecule is ionized, followed by its fragmentation. There, two competing mechanism may occur, i.e., dissociation by recollision with the ejected electron [2] or dissociation of the molecular ion [1]. Evaluation of these two mechanisms is a crucial step in the experimental understanding of the dissociation dynamics of the molecule. In this framework, accurate ab initio calculations of the potential energy curves (PECs) of the molecular ions may provide a valuable tool in support of the experiment. In this abstract, an accurate relativistic ab initio molecular approach is proposed to model the PECs or Ar 2+ in the electronic ground and lowest-lying excited states across a wide interatomic distance range up to the molecular dissociation limit. The approach, based on the relativistic

Fock- Space Coupled Cluster (FS-CC) level of theory, yields PECs which are in good agreement with both the experimental results and the available theoretical literature and substantially supports the experimental interpretation and investigation of the possible dissociation pathways of the molecular ion.

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C.25 Phase-space measurements of a buffer gas cooled BaF beam for the NL-eEDM experiment

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The search for the electric dipole moment of the electron (eEDM) is a direct test of fundamental theories beyond the Standard Model. We aim to perform a competitive measurement of the textiteEDM with a Stark decelerated and laser cooled beam of barium monofluoride (BaF) molecules[1]. I will present the work of the collaboration and particularly focus on the construction and optimization of a cryogenic beam source I have been working on. The density and rotational temperature of the beam are measured with rotationally resolved absorption and laser-induced fluorescence detection. We have developed a novel method to directly measure the phase-space distribution in the longitudinal (forward) direction of the molecular beam, using a two-step excitation scheme. Our source currently produces about 2×10^{10} molecules sr^{-1} per pulse in a single rotational level with a forward velocity of 200 m/s. With our method, we have carefully analysed the effect of many parameters in order to find the optimal parameters for producing the most intense molecular beam with the lowest possible velocity.

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C.26 A Global Approximation Interpretation of Quantum Mechanics

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Contrary to the common understanding of quantum mechanics, including amongst scientists, the basic concepts of quantum mechanics have been in bitter controversy from its inception until today. No one disavows the success of quantum mechanics, but that success comes from its formulation system or the mathematical tools it provides. However, the rudimentary concepts lay the foundation for the theory and allow little tolerance for dispute. People are still puzzled about the understanding of many quantum behaviors. Instead of the quantum wave function and measurement, we found that the properties and physical meanings of the Schrodinger equation are the keys to understanding all quantum behavior, i.e., the globality and the approximation of the equation, as well as the method of equation-solving. We can intuitively understand all quantum properties by putting back the omitted parts in the approximation without introducing any hypothesis but only the widely-accepted knowledge of fundamental interactions and elementary particles. Global Approximation Interpretation (GAI) explains well the quantum wave function, the origin of the probability interpretation, coherence, measurement, the boundary between the classical and quantum world, the emergence of quantization, the properties and the physical pictures of elementary particles, quantum entanglement, quantum eraser experiment, and more. GAI defines measurement based on interactions and finds that reality is relative. Formerly contradictory philosophical theories can reconcile, such as reductionism and holism, idealism and materialism, and determinism and indeterminism. The philosophical difficulties posed by the Copenhagen Interpretation are all gone.

C.27 Spectral properties of four-wave mixing in the four-level atomic system

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The interaction of three coherent light sources in the four-level atomic system under the ladder-V configuration is simulated using the density matrix formalism. The characteristics of the four-wave mixing (FWM) signal generated in this system are obtained and analyzed in view of the dressed state picture. This talk will discuss the dependence of the number of peaks, the peaks' position, height, intensity, and shape on the laser scanning scheme, the applied Rabi frequencies, and frequency detunings. We found that a notable increase in FWM intensity is achieved when the Rabi frequencies of two control fields are equal. The frequency detunings of the applied fields not only change the peak position and shape but also result in the FWM intensity enhancement. These spectral properties are well demonstrated and explained in view of the dressed state picture.

C.28 Single- and double-ionization processes of antiproton-helium and antiproton-molecular hydrogen collisions in the keV energy range

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We report on an ab initio model to describe single- and double-ionization processes in antiproton collisions with atoms and molecules. Our model is based on a fully correlated close-coupling approach and a Dyson orbital analysis. Furthermore, we employ the concept of a correlation integral in order to quantify and gain insights into the effects of electronic correlation on the ionization processes. Our model is applied to the prototype antiproton-helium and antiproton–molecular hydrogen collision systems in the keV energy range.

C.29 Heat rectification in ion crystals

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Heat rectification is the physical phenomenon, analogous to electrical current rectification in diodes, in which heat current through a device or medium is not symmetric with respect to the exchange of the baths at the boundaries. In the limiting case the device allows heat to propagate in one direction from the hot to the cold bath while it behaves as a thermal insulator in the opposite direction when the baths are exchanged.

In this work, we study heat rectification in linear chains of ions in trap lattices with graded trapping frequencies, in contact with thermal baths implemented by optical molasses. To calculate the local temperatures and heat currents we find the stationary state by solving a system of algebraic equations, a much faster approach than the usual method that integrates the dynamical equations of the system and averages over noise realizations. We also show that even though, in early times, some kind of anharmonicity, i.e. non-linear forces, in the substrate potential or in the particle-particle interactions, was identified as a fundamental requisite for rectification, asymmetric heat transport is found in this linear system if both the bath temperatures and the temperature dependent bath-system couplings are also exchanged. We demonstrate that it is the match/mismatch of the phonon bands (power spectra) the mechanism that governs the heat transport in the chain, allowing it when the bands match or obstructing it if they mismatch and we will present recent results directly relating the heat fluxes with the matching of the power spectra.

C.30 Probing properties of twisted light by the Hanle effect

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During recent years, a number of studies has been performed to investigate the operation of electric-dipole-forbidden transitions in trapped ions by twisted light modes. In particular, Laguerre Gaussian (LG) light was employed at the Physikalisch-Technische Bundesanstalt in Braunschweig to induce the electric octupole transition in an Yb^+ ion [1]. The analysis of this experiment was hindered by the fact that it was not possible to employ the incident radiation in a single pure LG mode. Indeed, the use of a vortex retarder allows one to produce the LG mode with well-defined angular momentum projections and polarization pattern which is contaminated, however, by a number of other modes, including plane wave radiation. In this contribution, we

theoretically propose a method to diagnose rather small admixtures of twisted (as well as plane wave) radiation to the leading LG mode. The method is based on the well-elaborated Hanle effect, that is the dependence of the magnetic sublevel population (and hence, of the angular and polarization properties of the fluorescence radiation) on the strength of an externally applied magnetic field. In the framework of the density matrix approach and the Liouville-von Neumann equation we show that the B-dependence of the magnetic sublevel population is very sensitive to the composition of the incident radiation. To illustrate this sensitivity we performed detailed calculations for the $5s^2\mathrm{S}_{1/2} - 5p^2\mathrm{P}_{3/2}$ transition in a rubidium atom induced by the LG_{10} mode with a small admixture of the LG_{00} mode. Based on the results of these calculations, we argue that even tiny admixtures of LG_{00} radiation may result in remarkable variation of the $5s^2\mathrm{S}_{1/2}$ sublevel populations, which opens up new opportunities for the diagnostics of twisted light in high precision atomic spectroscopy experiments.

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C.31 Compton Polarimetry on Rayleigh Scattering of Highly Linearly Polarized Hard X-Rays on Gold Atoms

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Rayleigh scattering is the dominant contribution to the fundamental photon-matter interaction process of elastic scattering of photons on atoms for photon energies below the MeV range [1]. This 2nd order QED process of a photon being scattered on a bound electron shows a strong anisotropy with respect to the polarization of incident and scattered radiation [2]. Thus, a stringent test of the corresponding theory can be performed by a precise measurement of the polarization transfer between incident and scattered beam.

For this purpose, we performed an experiment at the 3rd generation synchrotron facility PETRA III of DESY, Hamburg, where we scattered a highly linearly polarized hard x-ray beam with a photon energy of 175 keV on a thin gold foil. The polarization characteristics of the scattered beam were analyzed using a prototype 2D position-sensitive silicon strip detector, developed within the SPARC collaboration [3]. Exploiting Compton scattering in the detector crystal this detector serves as a dedicated Compton polarimeter [4].

In this contribution, both the concept of Compton polarimetry with the 2D position-sensitive detector and our experimental results in comparison with state-of-the-art calculations will be presented.

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C.32 Theory of the magnetic moments and hyperfine splitting of ^{3}He

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In an external magnetic field, the ground state of the $^3He^+$ ion is split into into four sublevels due to the combined hyperfine splitting and Zeeman effect. By measuring transition frequencies between these sublevels, it is possible to determine the g-factor of the bound electron, the ground-state hyperfine splitting as well as the shielded magnetic moment of the nucleus. In this work, we present the theoretical calculations of the nuclear shielding constant, the ground-state hyperfine splitting and the bound-electron g-factor [1]. The theoretical uncertainty of the bound-electron g-factor is dominated by the uncertainty of the fine-structure constant α. This would allow an independent determination of α in future, provided that the experimental precision can be improved accordingly. Combining the experimental value for the shielded nuclear magnetic moment and the theoretical value for the nuclear shielding constant, we extracted the magnetic moment of the bare nucleus with unprecedented precision, enabling new applications in magnetometry. Furthermore, we extracted the nuclear Zemach radius from the experimental hyperfine splitting value, in tension with the established literature value.

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C.33 3D quantum model of the photon

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The correct understanding of the nature of light has become particularly relevant in recent decades, when technologies for single photon generation and detection are intensively studied. The single photon is considered as the main element in quantum communication technologies. Quantum mechanics successfully explain the structure of atoms and molecules. For photon description, Paul Dirac in 1927 introduced a formal quantization procedure of Maxwell equations, which accurately describe the creation and annihilation of photons. It was very successful, but the physics of this procedure is not clear: what is there that oscillates and where are photons located in time and space? We constructed a new 3D model of photons using mathematics from the electromagnetic field quantization procedure and the soliton models of photons. Besides the interaction potential between the charged particle and the photons, which contains the annihilation and creation operators of photons, the new function for a description of free propagating photons is derived. This function presents the vector

potential of the field, the function is a product of the harmonic oscillator eigenfunction with the well-defined coordinate of the oscillator and the Gaussian function of the polar radius in the transverse direction. Our model does not contradict the quantization procedure and quantum mechanics, and, additionally, it describes reflection and refraction. But to be fully convinced of the validity of this proposed model, it needs to be further tested in various processes involving photons.

C.34 Nondipole-Induced Asymmetry in the Angular Distribution of Photoelectrons from Fixed-in-Space CO Molecules

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Nondipole effects make a significant contribution to the interaction of high-energy photons with matter. Usually, nondipole contributions lead to a forward-backward asymmetry in the photoelectron emission with respect to the propagation direction of light. Up to now, most nondipole studies were conducted for atoms or randomly oriented molecules. As a consequence, geometric characteristics and the position of objects in space were not taken into account. Here, we show how nondipole and scattering effects determine the final emission distribution from fixed-in-space CO molecule [1]. The experiment data at a photon energy of 905 eV were obtained using the COLTRIMS reaction microscope [2] available at beamline P04 of PETRA III, DESY. The calculations were carried out for O and C 1s-photoelectrons emission from fixed-in-space CO molecules in the frozen-core Hartree-Fock approximation using the stationary single center method [3]. We obtain that the main lobe in the emission distribution, which is pointing in the direction of the neighboring atom, systematically increases (decreases) by the nondipole terms when the scatterer points to the forward (backward) direction with respect to the light propagation. The present work provides a demonstration for the emergence of nondipole-induced asymmetry, which can be expected in future ultrafast photoelectron diffraction imaging experiments.

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C.35 Collective frequency shift of scattering off three-dimensional optical lattices

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A quantum many-body system featuring long range dipole-dipole interactions plays a key role in quantum information processing, quantum simulation, etc. It has been validated that neutral atoms serve as an excellent candidate for the study of many-body physics by their unique advantages, such as immune to external fileds, large dipole moment. Here, we proposed a new platform focusing on Strontium $5s5p^3P_2 - 5s4d^3D_3$ to explore the collective scattering off a three dimensional optical lattice via dipolar interactions. We calculated the magic wavelength for this transition around the range of 400 nm to 600 nm, which is 456 nm and 534 nm. By confining atoms in a Mott insulator of such an optical lattice, the interatomic distance is only half of the magic wavelength, which is more than one order of magnitude less than the transition wavelength. Such a ratio of the interatomic distance to the transition wavelength is satisficatory to the occurrence of dipolar interactions between atoms. By applying the coupled dipole model we captured the collective feature of the scattering off the lattice-trapped atoms. The result shows that the scattering strongly depends on the atom number and the interatomic distance. Specifically, the resonant frequency shift of the scattering can be two orders of magnitude of the natural linewidth of the transition (57 kHz) in a lattice with thousands of atoms. Furthermore, the dependence of the collective frequency shift on the laser polarization, the detection position has been investigated. This work not only enables us to understand the collective scattering feature due to dipolar interactions in an optical lattice, but also opens a new window for the study of many-body physics.

C.36 Towards a limit on the electron's electric dipole moment using BaF

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An improved bound on the electron Electric Dipole Moment (eEDM) as a measure for CP-violation will put strong constraints on extensions of the Standard Model. The NL-eEDM collaboration will use an intense, cold and slow molecular beam of heavy polar BaF molecules to conduct a precision measurement of the eEDM [1].

Characterization of our eEDM measurement setup is in progress, using a sensitive spin precession measurement in a supersonic beam of BaF molecules with velocities of 600 m/s, which passes through well-known E- and B-fields (10 kV/cm, 10 nT resp.). Currently, our work is focused on the experimental techniques employed to extract an eEDM limit and quantifying possible systematic effects.

Furthermore, to make use of the full beam flux for the eEDM measurement, the divergence of the slow molecular beam that exits the decelerator has to be reduced. To this end, we will be using two-dimensional

laser cooling, which we are currently setting up. The performance of the laser cooling will be tested on a molecular beam produced by a cryogenic buffer gas source and a hexapole lens.

Lastly, the performance of a separate cryogenic buffer gas source is analyzed.

In this poster, I will present progress on all fronts of the experiment, on behalf of the NL-eEDM project.

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C.37 Ionization, total and state selective charge exchange cross sections in fusion related collision systems – Significant improvement in the classical treatment of one-electron atomic systems with the addition of the Heisenberg correction

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The standard three-body classical trajectory Monte Carlo (CTMC) model is a well-known classical treatment for modelling atomic collisions. But due to the lack of quantum features in the standard model, the CTMC model is not able to describe accurately the cross sections mostly at lower impact energies when the quantum mechanics characteristic is dominant. Therefore, we developed a three-body quasi classical trajectory Monte Carlo (QCTMC) model taking into account quantum feature of the collision system, where the Heisenberg correction term is added to the standard classical Hamiltonian of the collision system to mimic the Heisenberg uncertainty principle [1-6].

We present ionization, total and state selective charge exchange cross sections in collisions between fully stripped ions with Hydrogen atoms at the impact energies between 5-200 keV/amu by using CTMC and QCTMC models. We found that our QCTMC model remarkably improves the obtained cross sections, especially at lower projectile energies. Our results are very close and are in good agreement with the previously obtained quantum-mechanical results. Our model with simplicity can time efficiently provide accurate results where maybe the quantum mechanical ones become complicated. Therefore, our model should be an alternative way to calculate accurate cross sections providing the same results as the quantum-mechanical approaches [1-6].

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C.38 Coulomb corrections to Delbrück scattering above the pair production threshold

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We present all-order calculations of Delbrück scattering for photon energies above the pair production threshold. Calculations are performed for the scattering of 2.754 MeV photons off plutonium atoms. The obtained results resolve the long-standing discrepancy between experimental data and theoretical predictions and demonstrate that an accurate treatment of the Coulomb corrections is crucial for the interpretation of existing and guidance of future Delbrück scattering experiments on heavy atoms [arXiv:2302.13643].

C.39 Probing Casimir-Polder Rydberg-Surface Interactions: Towards Extreme Near-Field Measurements

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In the near-field, the Casimir-Polder atom-surface interactions are described by $-C_3/z^3$ (where C_3 is the van der Waals coefficient and z is the atom-surface distance), corresponding to the interaction of the fluctuating atomic dipole with its surface induced image. The inverse cube law has been demonstrated with highly-excited (Rydberg) sodium atoms [1], while lower-lying excited atoms have been spectroscopically probed in vapor cells [2]. Rydberg atoms find now a renewed interest in quantum technology applications based on thin-cell platforms [3], due to exaggerated interactions with their environment.

Here we used selective reflection on a macroscopic cesium cell to probe Rydberg-surface dipole interactions. Atoms are first excited to the Cs($6P_{1/2}$) level and subsequently frequency modulated selective reflection is performed on the $6P_{1/2} \rightarrow nD_{3/2}$ or $6P_{1/2} \rightarrow nS_{1/2}$ transitions at 512nm (n 15-18). To analyze our experiments, we extend previous theoretical models [4] to account for the Maxwell-Boltzmann atomic velocity distribution. The estimated C_3 coefficient for the $16S_{1/2}$ state is 6 MHz μm^3 exceeding the theoretical prediction of 3.5MHz μm^3. We also performed Rydberg spectroscopy in thin-cells of thickness ranging from 50-1000nm [2]. Preliminary analysis of transmission spectra obtained between 250-700nm also provides a larger than predicted C_3 coefficient, consistent with our selective reflection experiment.

We are currently attempting to probe Rydberg atoms confined in smaller thicknesses, going towards extreme near-field measurements, where the atom-surface distance compares to the atomic size (the radius of our Rydbergs is 10nm). This could allow measurements of quadrupole interactions that scale as $-C_5/z^5$, with C_5

predicted to be 0.45kHz μm^5 for Cs($16S_{1/2}$).

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D Quantum technology applications of AMO Physics

D.1 Short-range interactions generating massive multipartite entanglement for metrology

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Multipartite entanglement is the key resource to push quantum metrology beyond the standard quantum limit imposed on systems of uncorrelated particles; and to explore the ultimate limits of measurement precision. Multipartite entanglement can be very effectively generated by infinite-range interactions among particles — yet the latter are literally realized only by coupling atoms (real or artificial) to a cavity mode; otherwise they can be effectively realized with contact interactions, but only in small atomic ensembles trapped in one or few spatial modes. Identifying entangling mechanisms beyond the infinite-range interactions is therefore of greatest interest, in order to use the native interactions in any quantum device as a resource. Here we focus on time-independent many-body Hamiltonians for qubits and qudits; and we theoretically show that massively entangled states possessing scalable spin squeezing can be generated by power-law interactions, as well as by genuinely short-range ones. This is achieved either via quantum quenches [1-3], or by driving the system with an external field [4]. Scalable squeezing rests upon an effective dynamical decoupling between collective spin degrees of freedom and spin-wave ones [3], giving rise to a dynamics analog to that of the infinite-range models; or it can rely on spontaneous breaking of a continuous symmetry, which allows a driving field to achieve scalable squeezing even when pushed to very small values [4]. These protocols open the route to achieve scalable squeezing in a vast range of quantum devices, including Rydberg-atom and trapped-ion arrays, superconducting-qubit arrays, or optical-attice atomic clocks.

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D.2 Dynamics of a coupled Ion-Nanowire Hybrid System

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Ultracold trapped ions in linear radiofrequency traps are well-established and highly controllable quantum systems with a variety of applications in fields such as precision spectroscopy, cold chemistry, quantum information and optical clocks. Nanomechanical oscillators are highly sensitive objects for the development and implementation of technologies in miniaturized devices. Their nanoscopic size makes them excellent candidates for the study of physics on the border of classical and quantum physics and highly susceptible to very weak forces. This property makes nanomechanical oscillators excellent measuring probes with high sensitivities that enabled the development of devices such as the atomic force microscopes. This project is aimed at the implementation of an ion-nanowire hybrid system to explore new methods of quantum state preparation, manipulation and readout via the mutual interaction of its constituents. A charged Ag_2Ga nanowire is positioned in close proximity to the trapped ions such that they experience a strong mutual Coulomb interaction. By mechanically driving the nanowire at its resonance frequency and matching it to a trapped ion's axial frequency, an efficient energy transfer from the mechanical nanowire motion to the ion motion is expected. Theoretical descriptions of the ion-nanowire resonant drive have shown an increase in the kinetic energy of the ions in a classical description, as well as the creation of highly excited coherent states in a quantum mechanical description in which the ion is initially prepared in its motional ground state.

D.3 Quantum rotation sensor with real-time readout based on an atom-cavity system

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Quantum sensing aims to take advantage of the accuracy and long-time stability of quantum platforms, such as ultracold atoms, for new technological applications. Using an atom-cavity platform, we propose to combine the effective gauge phase of rotated neutral atoms and the superradiant phase transition to build a highly sensitive and fast quantum rotation sensor. The atoms in a well-controlled array of Bose-Einstein condensates are coupled to a single light mode of an optical cavity. The photon emission from the cavity indicates changes in the rotation frequency in real time, which is crucial for inertial navigation. We derive an analytical expression for the phase boundaries and use a semi-classical method to map out the phase diagram numerically, which provides the dependence of the photon emission on the rotation. We further suggest to operate the sensor with a bias rotation, and to enlarge the enclosed area, to enhance the sensitivity of the sensor. Our proposal puts forth to create quantum rotational sensors not only for static high precision frequency measurements but also for inertial measurements and navigation, where the ability to measure time-varying signals is crucial.

D.4 Frustrating quantum batteries

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We are at the verge of the Quantum Technology Revolution: quantum mechanics allows for phenomena that have no classical counterparts and which can be harvested for new technologies. An example of the emerging quantum technologies are quantum batteries (QB), i.e. quantum mechanical systems that can store and transfer energy in a coherent way. While the practical implementation of such devices is still far from becoming reality, a serious effort is being devoted to understanding their advantages and limitations, using different platforms and protocols. As it has been recently demonstrated that the introduction of topological frustration in one-dimensional spin-1/2 chains can strongly modify the low energy properties of these systems, we investigate the performance of a quantum battery realized through such frustrated chains and introduce a novel, natural, decoherence mechanism that show their superiority compared to their unfrustrated counterpart. We quantify this superiority using the notion of ergotropy, that is, the amount of energy that can be extracted from a battery with a unitary transformation.

D.5 Evolutionary shaping of leakage-aware pulses for Rydberg blockade gates

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The Rydberg blockade is one of the most promising phenomenon to mediate interactions and entanglement between neutral-atomic qubits. The blockade strength can be increased by shooting for a high-lying Rydberg state, but it also opens up the possibility of state leakage towards undesired Rydberg states, which may compromise the whole gate due to their strong induced interactions with nearby atoms.

Instead of simply suppressing this leakage, we propose to integrate these other states in the setup, and optimise the pulse shape accordingly. This leaves to a very high-dimensional computational problem, with limited efficiency of analytical techniques. Thus, we propose to solve it with artificial evolution, a broad variety of algorithms dedicated to high-dimensional problems.

D.6 Generating multiparticle entangled states by self-organization of driven ultracold atoms

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We study a methodology for guiding the dynamical evolution of ultracold atomic motional degrees of freedom towards multiparticle entangled Dicke-like states, via nonlinear self-organization under external driving. Two examples of nonlinear many-body models are investigated. In the first model the external drive is a temporally oscillating magnetic field, leading to self-organization by interatomic scattering. In the second model the drive is a pump laser, leading to self-organization by photon-atom scattering in a ring cavity. We demonstrate highly efficient generation of multiparticle entangled states of atomic motion and discuss prospective experimental realizations of the models. Our results highlight the potential for using self-organization of atomic motion in quantum technological applications.

D.7 Optimizing Rydberg Gates for Logical Qubit Performance

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Improving the fidelity of two-qubit Rydberg blockade gates is one of the key challenges for the continued development of neutral atom quantum processors. Here, we employ quantum optimal control methods to construct a family of Rydberg blockade gates that are robust against two common, major imperfections: intensity inhomogeneity and Doppler shifts. These gates can be implemented with a global laser pulse, whose phase is modulated in time to achieve the desired robustness. While being robust against intensity inhomogeneity and Doppler shifts, the gates show an increased susceptibility to Rydberg decay errors. To quantify this tradeoff, we evaluate the gate fidelity for the example of erasure-biased metastable ^{171}Yb qubits, and find that the robust gates significantly outperform existing gates for moderate or large imperfections. We then consider the logical performance of these gates in the context of an error correction code. In this case, we observe that the robust gates outperform existing gates even for very small imperfections, because they maintain the native large bias towards erasure errors. Our results significantly reduce the laser stability and atomic temperature requirements to achieve fault-tolerant quantum computing with neutral atoms.

D.8 Development of an atomic magnetometer for space-borne biomagnetic measurements

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Optically pumped atomic magnetometers (OPMs) are among the most sensitive detectors for slowly varying magnetic fields, surpassed possibly only by superconducting quantum interference devices. They can be quite compact and do not need complex infrastructure for operation, regular maintenance and support personal. OPMs facilitate employment in common or even hostile environments, proven by their early space mission deployment. This combination makes OPMs applicable for healthcare in remote areas, on aircrafts and spacecrafts, where conventional methods are unavailable or impossible. Being essentially based on a high degree of atomic spin coherence, OPMs are subject to stringent constraints on the magnetic properties of the environment.

Those typically lead to efficient operation only in high-performance magnetic shields. Unshielded sensitivity is degraded by several orders of magnitude, compared to the level of quantum limits, which biomagnetic applications heavily rely on. We focus on OPMs, suitable for detection of pathological phenomena in human muscles. This application calls for sensitivity on the order of 100 fT/$\sqrt{\text{Hz}}$ in a 1000 Hz bandwidth, few millimeter spatial field resolution and possibly full information on the direction of the field of interest. We investigate how those parameters are influenced by slowly varying environmental magnetic fields and gradients thereof, as well as high frequency technical perturbations. We propose a high order gradiometric system in a half-open weak magnetic shield, with sensors actively tracing and controlling the magnetic field of arbitrary orientation, based on simultaneous observation of spin orientation and alignment. We implement the lab-scale prototype of the OPM system, demonstrating the performance sufficient for the application, yet suitable for the implementation in space-borne size-weight-power limits.

D.9 Observation of quantum correlations on the strontium optical clock transition

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Optical lattice clocks are currently among the most precise devices for frequency generation and measurement. A critical aspect of these clocks is frequency instability, which is now close to the standard quantum limit associated with the quantum uncertainty of coherent spin states of the uncorrelated atoms. This fundamental limit can be overcome by preparing spin-squeezed states in which the atoms exhibit quantum correlations, so as to further improve the frequency stability without requiring an increase in the atom number.

In this work, we demonstrate the generation of the spin-squeezed atomic state on the optical clock transition of neutral strontium using a cavity-enhanced quantum nondemolition measurement scheme. In the scheme, a probe laser with a large frequency detuning to the atomic resonance is coupled with the atoms, allowing for indirect measurement of the atom number in the clock ground state. The preserved coherence destroyed by the probe laser is estimated from the loss of contrast of Ramsey fringes. Consecutive quantum nondemolition measurements of the prepared atomic state on the clock transition show quantum correlations between the state measurements. These correlations yield a Wineland parameter value of 0.95 manifesting spin squeezing along with a conditional reduction of state measurement noises by 3.5 dB.

Further metrological improvement is expected by reducing free-space scattered photons and technical noise sources. The proposed scheme is compatible with the configurations of state-of-the-art optical lattice clocks, paving the way for further improvement in frequency stability.

D.10 Multidirectional magnetic field sensing using ground-state aligment in atomic Cs

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In the current study we present magetooptical signals based on angular momentum ground-state alignment that can be used to detect magnetic field in two orthogonal directions. We used two beams from a single laser source to create a pump-probe geometry [1] where the ground-state angular momentum alignment is created by a linearly polarized ($\mathbf{E_p}$) pump beam. When an external magnetic field ($\mathbf{B_z}$) is applied the angular momentum distribution changes and this change is probed by a second linearly polarized ($\mathbf{E_s}$) probe beam. Because $\mathbf{E_s}$ lies in the x-y plane and makes a $\pi/4$ angle with respect to $\mathbf{E_p}$ that is parallel to the y-axis, the absorption signal of the probe beam yields a dispersive dependence on the transverse magnetic field component $\mathbf{B_z}$. For the system to be sensitive to magnetic field along x-axis ($\mathbf{B_x}$) we rotate the polarization of the probe beam around its propagation direction $\mathbf{k_s}$ until the $\mathbf{E_s}$ lies in the z-y plane. We implement this rotation of the plane of polarization experimentally by the use of an electro-optic modulator. This enables us to detect two orthogonal components of the external magnetic field from a single experiment. Additionally, the implemented pump-probe geometry [1] leads to a more compact experimental setup because of the fact that the required angle between the pump ($\mathbf{k_p}$) and probe ($\mathbf{k_s}$) beams is 35.3 degrees which in turn means that the light from both beams can enter the vapour cell from the same optical port.

We have performed simulations of the absorption signals for various Cs D1 transitions and studied how the signal is dependent on the Rabi frequency. We have also obtained experimental signals with several combinations of pump and probe beam intensity ratios for all Cs D1 hyperfine transitions.

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D.11 Isolated Core Excitation: a new tool for the manipulation of quantum information with divalent Rydberg atoms

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New experimental platforms based on monovalent alkali atoms, individually controlled in optical tweezer arrays and excited to Rydberg states, have recently proven to be competitive quantum simulators [1]. Within this framework, a few teams have lately implemented alkaline-earth-like atoms such as Strontium and Ytterbium, in order to benefit from their specific two-electron internal structure, with very promising performances [2,3]. Perhaps the most exciting outlook offered by these species is the coherent optical manipulation of Rydberg states enabled by the presence of the second electron, a technique called isolated core excitation (ICE). This possibility was just demonstrated by the "Frozen Rydberg Gases" team at LAC [4] using its apparatus dedicated to the study of Rydberg excitations of ytterbium [5], opening new perspectives towards applications in quantum simulation and quantum computing.

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D.12 A comparative study of decoherence rates in alkali cells for applications in quantum memories

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Quantum communication over long distances is limited by photon loss. This problem could be overcome by quantum repeaters, which create long-distance entanglement via entanglement swapping and require a quantum memory (QM) to store the created short-distance entanglement. While there are several QM designs being investigated, the most technologically feasible design will be one that is compact, energy efficient, operating at near room temperature, and with large storage times. Recent research that can be found in literature points to near room temperature alkali vapor as one of the most promising systems for QM implementation [1]. One of the main limiting factors of alkali vapor based QM is a relatively high decoherence rate, which can be partially overcome by using coated-wall cells or noble gas-filled cells. In our work, we first carried out a comparative study of decoherence rates for rubidium vapor cells coated with paraffin and alkene, as well as for cells filled with neon gas, after which we examined their QM properties. Our quantum memory is realized using electromagnetically-induced transparency (EIT) in 85Rb vapor. Measurements of EIT bandwidth for various vapor cells show that the presence of a buffer gas reduces the decoherence rate by more than eight times compared to wall coated cells. Consequently, buffer gas filled cells show superior QM performance, i.e. longer storage times and higher efficiency. In order to avoid issues with absorption, we detune our QM slightly off-resonance. In this condition, using classical light, we were able to measure storage times of up to 1.2 milliseconds, with a maximum storage efficiency of 26%. This sets the groundwork for our future research based on single-photon QMs and multimode QMs using a frequency comb source.

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D.13 Enhancing Atom-Photon and Atom-Atom Interactions with Integrated Nanophotonics

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The combination of thermal atomic vapor with nanophotonic structures provides a unique testbed for the manipulation of atom-atom and atom-photon interactions. Those integrated devices additionally lever efficient atom-light interactions below the diffraction limit. In contrast to free-space interactions, atoms aligned within a slot waveguide experience repulsive interactions enhanced by a factor of eight due to the Purcell effect. This leads to a corresponding blue shift, as the atoms are arranged in an essentially one-dimensional geometry, which vanishes above the saturation, providing a controllable nonlinearity at the few-photon level [1]. In order to also measure the induced phase shift, we plan on using a 120° phase difference unbalanced Michelson interferometer composed of a 3x3 optical fiber coupler.

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D.14 Phase and frequency stabilization of diode lasers

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Technologies depending on controllable interactions between laser-light and an atom or an ion constitute a remarkable subset of the applications that quantum revolution has to offer where the utilization of the quantum mechanical concepts such as superposition and entanglement is of utmost significance. The coherent coupling between the atom and the laser-light leads to the evolution of the quantum state of the atom with an appropriate phase relationship in association with the laser field that is driving the transition. This permits one to generate and control arbitrary superposition states of the atomic energy levels by applying laser pulses of a specific power, frequency, and duration, consequently allowing to control the probability of finding an atom in the excited state. The ability to control well and finely tune this coherent coupling majorly influences the scalability and performance of quantum computers, and stability and precision of optical clocks and quantum sensors. Hence, a highly stable laser source is essential to the further development of quantum systems. In this poster, I discuss the concepts of laser locking and about TOPTICA locking solutions that provides exceptionally stable tunable diode lasers such as ECDL with the powerful electronics namely PDH with DLC pro, FALC pro, Digilock 110 that help to reduce remaining frequency and phase fluctuations.

D.15 A dual-atom interferometer for precision inertial sensing

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Light pulse atom interferometers are a promising tool to realize high precision inertial sensors to measure acceleration, rotation, and gravity with unprecedented accuracy. Introduction of simultaneous internal-state

transitions on each branch of an atom interferometer has the capability of being sensitive to the test of weak equivalence principle as well as measurement of gravitational red shift due to the rejection of common mode noise sources. In the poster, we will present our experimental setup and performance and some results towards realizing a dual-atom interferometer inertial sensor.

D.16 Robust control and optimal Rydberg states for neutral atom two-qubit gates

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Neutral atom quantum computers have emerged as a promising candidate for near term quantum computers. These computers utilize long-lived clock transitions for the qubit manifold and a less stable, auxiliary Rydberg state for generating entanglement. We identify two-qubit quantum gates that are robust to experimental deviations such as laser intensity and frequency noise on a short time scale, using techniques from quantum optimal control (QOC). We further calculate physical properties associated with infidelity for strontium-88 atoms, including lifetimes, polarizabilities and blockade strengths - and use these calculations to identify optimal Rydberg states for our protocols, which allows for further minimization of infidelity.

E Applications to astrophysics, plasma physics, biophysics, clusters, ...

E.1 Multi-Platform Atomic Data Calculations in Re III, IV, V: Application to Nuclear Fusion Research

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It is now well established that tungsten will be one of the main divertor components of the ITER nuclear fusion reactor. When the Deuterium-Tritium fusion will take place, very energetic neutrons will strike the walls of the reactor and will cause the transmutation of tungsten atoms by irradiation. The primary transmutation products for tungsten are rhenium, osmium and tantalum. In particular, the calculations revealed that, after 5-year irradiation under first wall fusion power-plant conditions in ITER, Re, Os and Ta would reach concentrations of 3.8, 1.4, and 0.8 atomic percentage, respectively. As with tungsten, during fusion operations, these atoms, and more particularly rhenium atoms, will be torn from the reactor wall and enter the plasma where they will be impurities contributing to the energy loss by radiation but can also be used for plasma temperature and density diagnostics from the analysis of their spectra in all ionization stages. Therefore the radiative properties of these ions have potential important applications in this field. The purpose of the present work is to provide a new set of atomic data (oscillator strengths and transition probabilities) for electric dipole lines in rhenium ions, from Re III to Re V, obtained using two independent theoretical approaches, i.e. the pseudo-relativistic

Hartree-Fock (HFR) and the fully relativistic Dirac-Hartree-Fock (MCDHF) methods. Preliminary results will be shown at the conference.

E.2 Two-photon- and magnetic dipole one-photon absorption in atomic iodine for temperature and atomic density diagnostics in low-temperature plasmas and a revision of the energy levels of I I

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In the context of a rising use of iodine, as an alternative to xenon, in plasma thrusters, different optical methods have been characterized, for iodine-plasma diagnostics. First, two-photon absorption laser induced fluorescence (TALIF) of the (3P2)6p 2[1]3/2 and (3P2)6p 2[3]7/2 excited levels of atomic iodine had its possibilities tested. The radiative lifetime of the (3P2)6p 2[1]3/2 level was found equal to 35.5(9) ns, which appears consistent with the 32.5(1.2) ns predicted by recent calculations. The use of an injection-seeded pulsed laser as the primary laser source, the frequency-tripling of which has provided the ca 300 nm radiation used for two-photon excitation, made it possible to implement a Doppler-free two-photon excitation scheme and check that the relative intensities of the hyperfine components follow standard formulas. One could thus disentangle the hyperfine structure of the two-photon line from Doppler broadening and use TALIF to accurately measure the translational temperature of the atoms. Additionally, absolute energy measurements have led to revise the energies of all upper energy levels of atomic iodine by $-0.169(11)$ cm^{-1}, which has appeared all the more remarkable that tabulated values of the energy levels of iodine have been presented for half a century as having a ± 0.005 cm^{-1} accuracy. A second method for diagnostics has relied on excitation of the electric dipole-forbidden 5p5 2P3/2$\rightarrow$5p5 2P1/2 fine-structure transition, inside the ground term of iodine, at 760298 m^{-1}, i.e., 1315 nm. Together with a value of the molecular dissociation ratio deduced from observed molecular absorption at 488 nm, the absorption rate measured on one selected hyperfine component of the 1315 nm line made it possible to determine the population of both fine-structure levels.

Ref.: J. Phys. B: At. Mol. Opt. Phys. 56 (2023) 055002 (13pp).

E.3 Protein structure and dynamics using X-ray free-electron lasers - pitfalls

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X-ray crystallography has tremendous impact on biology, having yielded the structures of thousands of proteins and given detailed insight into their working mechanisms. The requirement for macroscopic crystals, which can be difficult to obtain, as well as the often severe radiation damage caused by the ionizing X-rays during data acquisition - in particular when using small crystals - has been relieved with the advent of X-ray free-electron lasers (XFELs). With their highly brilliant short X-ray pulses XFELs enable room temperature measurements, allowing to perform time-resolved experiments at atomic resolution at the chemical timescale of femtoseconds. More than ten years have passed since the Linac Coherent Light Source opened its doors to users.

Since then a great deal of technical development has taken place, allowing to gain new scientific insight. More XFEL facilities have come online, including the first MHz facility. Time to reflect on lessons learned, pitfalls, and to think about future challenges. The talk focusses on pump probe experiments.

E.4 Theoretical study of iodine ion-ion collisions in the context of spacecraft propulsion

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Spacecraft electric propulsion provides a low thrust for a long period of time, which is particularly useful for interplanetary missions or for satellites trajectory correction maneuvers [1]. Recently, a new type of electric thruster was developed using iodine as a propellant. An iodine plasma is formed and an electric field expels ions from the reactor thus creating a thrust. The iodine has the advantages over other types of propellant (like Xenon) of being easy to store in a solid form and to be cheaper. The first launch of a satellite using iodine plasma took place recently (on November 6, 2020) with a thruster developed by the French start-up ThrustMe on a satellite of the Chinese aerospace company SpaceTy [2]. The development of more efficient iodine thruster is impeded by the lack of knowledge about the chemical properties of the iodine plasma [3]. In this work, our objective is to compute the cross-sections of the most important chemical reactions occurring in the plasma, in order to use them in a global kinetic model describing the plasma. In order to compute these cross-sections, we employ advanced relativistic electronic structure calculation [4] to obtain the relevant potential energy surfaces, and then a semi-classical dynamic method (i.e. Landau-Zener surface hoping [5]). I will present our first results concerning the neutralization reaction I+ +I− →2I. This is a particularly important reaction since it reduces the amount of ions in the plasma and thus lowers the number of species that could be used for propulsion. Our results are in accordance with experimental measurements that were carried out in the ion ring DESIREE in Stockholm [6]. I will also give details about our current work concerning the I2+ +I− →3I reaction.

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E.5 Progress in polarization of ^{3}He atoms in a magnetized plasma (PAMP)

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Hyperpolarization techniques are relevant for all areas where an enormous boost in sensitivity is desirable. The recently discovered PAMP method (polarization of atoms in a magnetized plasma) yields sizeable ^{3}He nuclear polarization at various high magnetic field strengths, simply by firing a rf discharge in the gas [1]. PAMP appears as a promising alternative to laser optical pumping techniques [2]. Further exploration of PAMP and firm establishment of its mechanism are needed. Progress towards these objectives will be reported. A description of PAMP involving alignment-to-orientation conversion in the excited 2^3P state has been proposed [1]. In Paris, numerical toy models were developed to test this scenario and to infer the expected field dependence of steady-state ^{3}He polarization. Investigations involving absorption-based spectroscopy and polarimetry in the gas discharge were launched at moderate field strength. A collaboration was also established with a team in NIMBE/CEA-Saclay to allow in-depth PAMP studies with dedicated NMR and optical tools, hosted by a superwide bore 7-T NMR instrument [3]. In Kazan, a new series of PAMP measurements in sealed ^{3}He gas cells was performed at 3.66 T, from room to 200°C temperature, with gas filling pressures in the few millibars range and rf powers of up to 60 W [4]. Nuclear polarization build-up was monitored by NMR. Simultaneously, the optical fluorescence spectrum of the plasma and the cell temperature were recorded. A ^{3}He polarization as high as 8% percents was reached. Correlations between steady-state polarization values and measurements of the atomic oxygen impurity number density and of the cell temperature were observed.

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E.6 The role of the 3 → 5 excitation channels in the dielectronic recombination of M- shell Fe ions: the Na and Mg isoelectronic sequences

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The important role played by dielectronic recombination (DR) of M-shell Fe ions in the observed absorption X-ray spectra of Seyfert galaxies [1,2] have encouraged a thorough investigation of the related plasma DR rate coefficients in support of astrophysical observations. So far, theoretical modeling of such processes has accounted for the sole contributions due to $\Delta n = 0, 1$ excitation channels (see, for instance, [1]). However, it was pointed out that at reasonably high temperatures even the neglected $\Delta n = 2$ channels may remarkably contribute to the total temperature-dependent DR rates [3]. This has spurred us to investigating the contribution of the $\Delta n = 2$ excitation channels for the $3 \rightarrow 5$ electron excitations to the plasma rate coefficients of initially Na-like and Mg-like Fe ions in the 105 - 109 K temperature range, by means of the Multi-Configurational Dirac-Hartree-Fock method. As a result, the contribution to the total plasma DR rates due to this excitation channel was found to be relevant and comparable to he $\Delta n = 0, 1$ analogs.

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E.7 Determination of mercury in wild bird samples by Zeeman atomic absorption spectrometry

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Mercury is one of the most dangerous and poisonous heavy metals and is widely distributed in the environment. It is toxic in all its forms. However, the main danger of mercury is its most popular organic form – methylmercury, and in so-called bioaccumulation and biomagnification processes in the food chain. Our work is dedicated to accurate measurement of Hg in biological samples of birds (mostly the Black stork) in order to draw conclusions about the distribution of mercury in the environment. Hg monitoring with birds may be done by using various indicators, such as eggshells, inner membranes, faeces. For this study very sensitive technique – the Zeeman atomic absorption spectrometry with high-frequency modulation of light polarization – was used. The use of the Zeeman background correction and a multi-path analytical cell provides high selectivity and sensitivity of measurements. One of the main components of the equipment is a high-frequency electrodeless discharge lamp, filled with mercury isotope vapor (pair isotope ^{198}Hg or ^{204}Hg). The lamp is placed in permanent magnetic field. Comparison of the intensities of the σ-components allows to determine the concentration of mercury present in the analyzed sample. For the analysis of solid and biological samples, an attachment for thermal decomposition can be used. As a result, the instrument allows direct determination (no pre-treatment is required) of mercury in biological samples with a low detection limit of 1-3 ng/g. Analyzing 320 samples, it was found that Hg concentration in eggshells is on average 15 ng/g, with the highest values around 130 ng/g, whereas for membranes the average concentration is 200 ng/g, but there are elevated values exceeding 1500 ng/g. Under current legislation in Latvia, the maximum permissible concentration of mercury in surface water biota is 20 ng/g.

E.8 Numerical Studies of the Impact of Electromagnetic Field of Radiation on Valine

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We investigated theoretically and numerically the effect of the electromagnetic field of radiation on the valine molecule, which was further compared to previously existing experimental results for the interaction of valine with a high-energy electron beam. The theoretical calculations were performed with the quantum chemistry GAUSSIAN09 package and included geometry optimization of the structures of valine using the B3LYP/cc-pVTZ approach. Furthermore, we applied the method of Anisotropic Gaussian-type Orbitals and introduced correction coefficients to the $s-, p-$ or only $p-$ orbitals in a modified cc-pVTZ basis set, as a way to incorporate the effect of the magnetic field of radiation in the molecular wave functions. Using both the original and modified basis sets, a comparison of the bond length, angle, dihedral angles and fragmentation was performed, without and with the inclusion of the dipole electric and magnetic fields. The magnetic field impact was clearly seen, showing variations of up to 4 degrees in the values of the dihedral angles, as well as changes in the dipole momentum projection onto the $y-$ and $z-$ axes, when the magnetic field effects were taken into account. The influence of the magnetic field was also crucial in the fragmentation processes, proving that the fragments formed with the inclusion of the magnetic field were different to those formed without it (e.g., the CHO_2 fragment was seen only when the correction coefficients were included in the basis set of the $p-$ orbitals). Our numerical calculations, taking into account the impact of the magnetic field of radiation, provide a better fit with the experimental data, and thus, can be used as a tool for more accurate predictions and analysis of present and future experimental outcomes.

E.9 DESIREE: Mutual neutralization experiments

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The double electrostatic ion-beam storage ring, DESIREE, at Stockholm University is a facility for studies of atomic, molecular and cluster ions and their mutual interactions. The cryogenic conditions offered result in an extremely high vacuum, which enables studies of systems that need long times to relax. One recent series of mutual-neutralization experiments have focused on reactions involving hydrogen anions. Due to their high abundance in stellar atmospheres, MN involving these ions have significant influence on the observed absorption spectra, and a detailed understanding of these processes is therefore needed for precise determinations of abundances of other elements from the observed spectra. With DESIREE, we are able to determine the distribution of final states formed in MN, and we have done so for a number of collision systems already. Recently, we have made use of the combination of the merged-beams geometry for the two stored beams and the ability to store ions for long time to perform MN for ions with active control of their initial states. Results of a proof-of-principle experiment with silicon anions and sodium cations will be presented.

E.10 Magneto-optical filters using atomic filters: from Hamiltonian to application

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The interaction of atoms and light is of essential importance in many areas of physics, and a quantitative understanding of this interaction is therefore beneficial for a variety of reasons, both from the point of view of fundamental physics and for designing applications. We have developed a detailed numerical model [1] of the electric susceptibility (ElecSus) for alkali-metal vapours that calculates transition strengths and frequencies, and accounts for applied magnetic field, Doppler broadening, and several other experimental effects. ElecSus can be used as a tool to fit experimental data or predict novel effects and has already found use in designing an atomic optical isolator [2] and a single-mode external cavity laser using an intra-cavity MOF [3]. Here we explore one particular application of ElecSus; Magneto-optical filters (MOF). A MOF is a high-contrast, ultra-narrow bandpass filter that utilises the birefringent and dichroic properties of atomic media in an applied magnetic field. The filter's transmission profile is strongly dependent on the magnetic field strength and the atomic number density. ElecSus has been used to optimise the performance of such filters, and we see excellent agreement between theory and experimental data [4]. Finally, we explore a further application of MOFs in the context of space weather monitoring. Using two cascaded MOFs [5] and by carefully engineering the optimal conditions for the MOF performance, it is possible to extract the solar magnetic field from the Zeeman-split Fraunhofer lines [6].

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E.11 Determination of the radiative properties of Ta VII using a multiplatform approach

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Tantalum (Z=73) is an element that is produced in neutron-induced transmutation of tungsten (Z=74) which in turn will compose the divertors in Tokamaks (Gilbert & Sublet, Nucl. Fusion 51, 043005, 2011). As a consequence, their sputtering may generate ionic impurities of all possible charge states in the deuterium-tritium plasma that could contribute to radiation losses in controlled nuclear devices. The radiative properties of these ions have therefore potential important applications in this field. In this context, a multiplatform approach has been adopted in order to compute the Ta VII radiative rates and estimate their accuracy. The oscillator strengths and transition probabilities have been calculated for the 237 E1 lines in Ta VII as classified in 2014 by Ryabtsev et al. (Phys. Scr. 89, 125403, 2014) . Three independent atomic structure models have been used; one based on the semi-empirical HFR method and two based on the ab initio MCDHF method.

E.12 Expansion and line-binned opacities of samarium ions for the analysis of early kilonova emission from neutron star mergers

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Opacity calculations performed within the expansion and the line-binned formalisms are reported for Sm V-X ions in the present paper. These were determined by means of new large-scale atomic structure and radiative rate computations carried out using the pseudo-relativistic Hartree-Fock (HFR) method from which energy levels, wave- lengths and oscillator strengths were deduced for more than 100 millions of spectral lines in the considered samarium ions. In the absence of any experimental data, the reliability of HFR results was roughly estimated by comparison with those obtained with an independent theoretical approach, namely the fully relativistic multiconfiguration Dirac-Hartree-Fock (MCDHF) method, in Sm VI and Sm VII. The opacities were estimated for typical conditions corresponding to early phases of kilonovae following neutron star mergers, i.e. for a density equal to 10^{-10} g cm^{-3}, a time after the merger $t = 0.1$ day and temperatures ranging from 25000 to 70000 K. In addition, the atomic calculations allowed us to establish the ground level for each of the Sm ions considered, (still unknown until now), as well as reliable partition functions which are crucial for the determination of relative ionic abundances by solving the Saha equation and for accurate opacity calculations.

E.13 Atomic data and expansion opacity calculations in two representative 4d transition elements, niobium and silver, for the spectral analysis of kilonovae

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Neutron Star (NS) mergers are thought to be a source of heavy trans-iron element production. The latter can be detected in the spectra of the ejected materials, from which a bright electromagnetic radiation due to

the radioactive decays of the produced heavy r-process nuclei and known as kilonova is emitted. Because of their complex atomic structures characterized by configurations involving unfilled nd or nf subshells, the heavy elements of the kilonova ejecta often give rise to numerous absorption lines generating significant opacities. The determination of the latter, which are of paramount importance for the analysis of kilonova light curves, requires the knowledge of radiative parameters for the largest possible number of spectral lines belonging to the ions expected to be present in the kilonova ejecta. The aim of the present work is to provide new atomic opacity data for two representative 4d elements, niobium (Nb) and silver (Ag), in their first four charge states, i.e. for Nb I-IV and Ag I-IV. Large-scale calculations based on the pseudo-relativistic Hartree-Fock (HFR) method were performed to obtain the atomic structure and radiative parameters while the expansion formalism was used to estimate the opacities. Wavelengths and oscillator strengths were computed for several millions of spectral lines in Nb I-IV and Ag I-IV ions, the reliability of these parameters having been estimated by comparison with the few previously published experimental and theoretical results. The newly obtained atomic data were then used to calculate expansion opacities for typical kilonova conditions expected one day after NS merger, a density of 10^{-13} g cm^{-3} and temperatures ranging from T=5000 K to T=15000 K.

E.14 Influence of rotational and collision energy on the reaction rate of the D_2^++NH_3 reaction

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Low-energy ion-molecule reactions are difficult to study because stray fields heat the ions up. This difficulty is circumvented by replacing the ion (here D_2^+) by a highly excited Rydberg molecule [1,2]. The distant Rydberg electron shields the ion core from external fields without influencing the ion-molecule reaction within its orbit. We use a Rydberg-Stark deflector to merge a beam of D_2 Rydberg molecules with a supersonic beam of NH_3 or ND_3 [3]. This deflector is also used to set the velocity of the Rydberg molecules vRyd. By tuning vRyd relative to vneutr, we tune the collision energy Ecol from $\sim$ kB 100 mK to $\sim$ kB 70 K. The product ions, the reaction rates and the branching ratios are measured as a function of Ecol. Short ($\sim$ 20 µs) gas pulses ensure a high collision-energy resolution. We adjust the rotational temperature (Trot) of the NH_3 beam by seeding in helium. We observe two reaction channels (NH_3^+ and NH_2D^+). The rate coefficients deviate strongly from Langevin rates and increase sharply below 2 K. They also increase as Trot is increased from 14 K to 39 K. These observations are interpreted by rotational adiabatic channel calculations as arising from the linear Stark effect of the two inversion tunneling components of ammonia in the ion electric field [4,5]. We compare these results with those obtained for the He^+ + NH_3 [5] and Rg^+ + NH_3 reactions [6].

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F Frequency and time domain spectroscopy and metrology

F.1 Ramsey interferometry with optimally twisted states and measurements

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We consider a variational class of generalized Ramsey protocols with two one-axis-twisting (OAT) operations, one before and one after the phase imprint, for which we optimize the direction of the signal imprint, the direction of the second OAT interaction and the measurement direction via a numerical routine for global optimization of constrained parameters. In doing so, we distinguish between protocols whose signal from spin projection measurements exhibits a symmetric or anti-symmetric dependence on the phase to be measured. We find that the Quantum Fisher Information, which bounds the sensitivity achievable with a one-axis-twisted input state, can be saturated in our variational class of protocols for nearly all initial squeezing strengths. Therefore, the generalized Ramsey protocols considered here allow us to reduce quantum projection noise in comparison to the standard Ramsey protocol considerably.

F.2 Planetary states of the Sr atom

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Because the quantum numbers of high lying doubly excited (planetary) electronic states can be controlled in a precise manner, the motion of two highly excited electrons in the field of the nucleus can be studied in great detail. By fine-tuning electron correlations, the fascinating transition from independent-electron dynamics to a strongly correlated behavior is investigated both in the time and frequency domains.

We have undertaken a systematic experimental and theoretical exploration of the high lying doubly excited of Sr. The strength and spatial extent of electron correlations is controlled by the degree of excitation of the core electron (N) and the principal- and orbital-angular-momentum quantum numbers (n, l) in which the Rydberg electron is first prepared. In the laboratory, multiphoton isolated-core excitation of alkaline-earth atoms is used to prepare atoms in doubly excited states in a controlled manner. Theoretically, we treat the increasing strength of electrons correlations as the core is excited with configuration interaction with exterior complex scaling, which allows a direct visualization of correlated electron dynamics.

Near the $N = 5$ ionization threshold, long-range electron correlations lead to a breakdown of the independent-electron picture, visible in the spectra through the excitation of entire Rydberg series that are not coupled to the initial state by independent-electron electric-dipole selection rules. For higher core excitation near the $Sr^+(7d)$ and $Sr^+(8p)$ ionization thresholds, the inner electron is strongly polarized by the electric field of the slow outer electron. The two electrons describe a planetary-type motion where they orbit the nucleus either on

the same side or on opposite sides, depending on the sign of the core polarizability. The investigation of yet higher core excitation, and therefore stronger electron correlations, is under way to further our understanding of the transition of three-body quantum dynamics from the independent-particles case to the strongly correlated regime.

F.3 Ultrafast electro-optic fractional Fourier imaging at the single-photon level

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The time-frequency (TF) domain is not only a pillar of modern optical communication, but also a prominent direction of development in emerging quantum technologies [Phys. Rev. X 5, 041017 (2015)]. TF-based quantum frameworks will require scalable methods for coherently transforming and selectively detecting TF modes. Here we present a modern experimental implementation of an important TF transformation - the fractional Fourier transform (FRT). FRT can be thought of as an arbitrary rotation by angle α in the TF phase space, with the ordinary Fourier transform being the special case of $\alpha = \pi/2$. Optical TF implementations of FRT are often based on a sequence of 1. dispersion (spectral quadratic phase) 2. time-lens (temporal quadratic phase) 3. another dispersion. In contrast to approaches based on non-linear interactions (cross-phase modulation, wave-mixing) which inherently introduce optical noise, we use precisely controlled electro-optic time-lens, rendering the setup single-photon-level compatible. Spectral dispersion is introduced with diffraction grating stretchers. We demonstrate a range of FRT angles beyond $\alpha = \pi/2$ with a precise all-electronic selection of α, for single-photon-level pulses of ca. 11.5 ps FWHM, with the maximal theoretical bandwidth of ca. 250 GHz. The indirect measurements are obtained via single-photon spectral interferometry for a pair of temporally separated coherent pulses exhibiting spectral fringes. With rapidly developing on-chip electrooptic modulators and fiber Bragg gratings, such an FRT implementation promises miniaturization and excellent scalability. Together with single-photon-level compatibility and all-electronic control, FRT constitutes a prominent building block of TF transformations, in particular for the synthesis of arbitrary unitaries or mode sorting.

F.4 Polarization dynamics in an alkali-noble gas comagnetometer

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Self-compensated comagnetometers, employing overlapping samples of spin-polarized alkali and noble gases (for example K- ^{3}He) are promising sensors for exotic beyond-the-standard-model fields and high-precision metrology such as rotation sensing. When the comagnetometer operates in the so-called self-compensated regime, the effective field, originating from contact interactions between the alkali valence electrons and the noble-gas nuclei, is compensated with an applied magnetic field. In the self-compensation regime the noble-gas magnetization follows changes in the low-frequency external magnetic field, which protects the alkali-metal polarization from the magnetic-field perturbation. However, this protection does not extend to nonmagnetic

perturbations (e.g. rotation or exotic spin couplings), allowing the measurement of such perturbations. When the comagnetometer begins operation in a given magnetic field, spin-exchange optical pumping establishes equilibrium between the alkali electron-spin polarization and the nuclear-spin polarization. Subsequently, when the magnetic field is tuned to the compensation point, the spin polarization is brought out of the equilibrium conditions. This causes a practical issue for long measurement times. We report on a novel method for closed-loop control of the compensation field. This method allows optimization of the operating parameters, especially magnetic field gradients, despite the inherently slow (hours to days) dynamics of the system. With the optimization, higher stable nuclear polarization, longer relaxation times and stronger electron-nuclear coupling are achieved which is useful for nuclear-spin-based quantum memory, spin amplifiers and gyroscopes. The optimized sensor demonstrates a sensitivity comparable to the best previous comagnetometer but with four times lower noble gas density. This paves the way for applications in both fundamental and applied science. Estimate of the comagnetometer sensitivities to neutron and proton exotic spin couplings in view of ultralight bosonic dark matter searches are presented.

F.5 Rb microfabricated cells for a two-photon optical frequency reference

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Miniaturized vapor cell optical clocks based on the use of the two photon absorption transition (TPT) of the Rb atom at 778 nm have recently demonstrated remarkable stability results. In such experiments, the presence of impurities in the vapor cell induces collisional broadening (several MHz/Torr) of the probed optical transition. Thus, achieving a cell inner atmosphere with high-purity is of crucial importance to fully explore the potential of the TPT natural linewidth ($\sim$ 300 kHz). In this work, we report on first characterization studies of pill dispenser-based Rb micro-fabricated cells, developed at FEMTO-ST. These microcells are fabricated similarly to Cs microcells, but use Rb dispenser pills instead. We have implemented a table-top setup for TPT spectroscopy at 778 nm, using an external cavity diode laser. Resonances detected in MEMS cells can be compared to those obtained in a reference glass-blown vapor cell. We assess the Rb cell purity by measuring the Lorentzian broadening of the TPT resonance linewidth. The reference cell resonance was measured to be broadened by 250 kHz, attributed to helium permeation from the surrounding air. The microcell showed a Lorentzian broadening equal to 2 MHz, revealing the presence of impurities, other than helium. These observations confirm that the measurement of the TPT resonance is a useful non-destructive method to test the level of purity of vapor microcells. We also demonstrate preliminary stability results of an optical frequency reference at 778 nm based on such a MEMS Rb cell. The Allan deviation is below 10^{-12} at 1 s and reaches 2.5×10^{-13} at 100 s. Cells with integrated non-evaporable getters might be tested in the near future.

F.6 Excitation mechanisms for the ^{229}Th isomer

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Amongst all nuclei, the ^{229}Th nucleus has the lowest first excited state at around 8 eV making it accessible with VUV light. The transition from the ground to the excited state has a radiative lifetime of a few hours and presents $M1/E2$ multipole mixing in which the $M1$ channel strongly dominates [1]. These unique properties make ^{229}Th an ideal candidate for a nuclear clock with outstanding properties. However, a hindrance towards its experimental realization is the relatively large uncertainty on the transition energy and the lack of narrowband VUV lasers.

In the first place, we investigate theoretically two different approaches to indirectly populate ^{229}Th's isomeric state. The first approach deals with quantum optical transfer schemes involving STIRAP and π-pulses via the second excited state at 29.19 keV at the Gamma Factory [2]. The second approach considers Electronic Bridge (EB) schemes in a VUV-transparent crystal environment doped with ^{229}Th. Here, EB involves electronic defect states which appear in the band gap due to ^{229}Th doping [3]. We present different EB schemes and the corresponding excitation rates for ^{229}Th:LiCAF.

Once a more accurate determination of the transition energy is achieved, one may proceed with resonant driving and metrology applications of ^{229}Th. For this purpose, we also study theoretically the interaction of ^{229}Th with twisted light carrying orbital angular momentum promising the accessibility of dipole forbidden transitions [4].

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F.7 Accurate bootstrapping of an optical frequency comb to the REFIMEVE 1542 nm reference

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Networks of optical fiber links disseminating time and frequency signals have revolutionized the capacity of remotely comparing and synchronizing instruments. In France, the REFIMEVE research infrastructure is jointly operated by LPL (Laboratoire de Physique des Lasers) and SYRTE (SYstèmes de Référence Temps-Espace, Observatoire de Paris). It allows the ultra-low noise, fiber-based, dissemination of an ultrastable carrier at 1542 nm to academic institutions, state agencies and industrials. We first present the source of this 1542 nm carrier, located at SYRTE together with the 7 French atomic clocks contributing to operational timescales. The phase lock to the reference maser allows the dispatching of an accurate frequency to all REFIMEVE users, with a dissemination noise negligible after a few seconds. This frequency features an instantaneous relative accuracy of a few 10^{-14}, that can be pushed down below 10^{-15} for longer integration times. Second, a consequence of knowing precisely the received frequency is that users may synthesize locally references at e.g. 10 MHz or 1 GHz. This is achieved with an optical frequency comb locked exclusively to the 1542 nm reference, without any need for additional inputs. We present our approach to this technique, known as 'bootstrapping', to generate RF

signals by frequency division. We describe the few mathematical solutions, we demonstrate the agreement of the resulting signal with the reference maser (below the 10^{-16} level), and we show its operational capacity to compare state-of-the-art optical clocks. Finally, we use this bootstrapping approach locally to frequency-divide the 1542 nm carrier down to a microwave signal at exactly 11.98 GHz with the frequency combs. This source will progressively replace the signal of our cryogenic sapphire oscillator, that was stopped in May 2022 following the ongoing worldwide Helium shortage, due to the international situation. We will present preliminary comparisons of this signal to the SYRTE microwave Cs and Rb fountains.

F.8 Ten quectonewton local force sensor with atom interferometry

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Atom interferometers are exquisite tools for force measurements such as gravity. However, state-of-the-art such sensors use free-falling atoms and hence cannot perform purely local force measurements. Instead, we use here optically trapped atoms to perform force sensing close to the surface of a mirror and probe with unprecedented sensitivity atom-surface interactions.

We start with a non-degenerate sample of ultracold ^{87}Rb atoms, which we transport at the vicinity of a mirror with a moving optical lattice. We end up with a 3.5 µm wide atomic cloud at a tunable distance of the mirror, with a position stability of less than a micron.

We then trap them in a mixed optical trap, combining a blue detuned static lattice and a red detuned progressive wave. Inside this trap, we induce laser assisted tunnelling between Wannier-Stark states with Raman laser pulses. This allows us to create a Raman Ramsey interferometer sensitive to the external force applied onto the atoms and to perform force measurements at different distances of our mirror with a sensitivity of 5×10^{-28} N at 1s and less than 10^{-29} N on the long-term. We actually measure an attractive force, with a maximum strength of order of 1.4×10^{-27} N, where the expected Casimir Polder force amounts in our conditions to 0.5×10^{-27} N. This force in excess arises from stray electric fields produced by charges or adsorbed atoms. These parasitic forces can be precisely determined in our setup by applying controlled additional electric fields thanks to electrodes placed around the mirror. Ideally, they would be suppressed by eliminating the spurious charges and adsorbed atoms, for instance by using UV illumination or by heating the mirror.

The sensitivity of our sensor opens new perspectives for precise measurements of Casimir-Polder force and other atoms-surface interactions.

F.9 Diatomic molecular vibrations in a strong infrared laser field: an analytic treatment of the laser-dressed Morse potential

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Diatomic molecules driven by strong laser pulses show a rich variety of fundamentally important processes, depending on how the laser pulse parameters are related to the diatomic's properties. Although the theoretical framework for molecules interacting with laser fields is well established, analytic methods are rare and approximate in the strong-field domain, while most of the numerical methods have heavily increasing cost for infrared (IR) wavelength.

In this contribution we present a general mathematical method to treat a Morse potential in the presence of a strong IR excitation. The dipole moment function in the Hamiltonian includes the permanent and the field-induced terms and their gradients, which is verified by density-functional theory calculation. Therefore, our model can be applied both to heteronuclear and to homonuclear diatomic molecules and to certain (e.g. alkali metal) atomic dimers. As a possible use we apply our procedure to H_2 and LiH and we show how an IR laser field in the intensity range of 10^{13} W/cm^2 noticeably shifts the vibrational levels and the equilibrium internuclear distance of the molecules. According to our results, the dipole gradient and the polarizability gradient are the essential molecular parameters in these effects. We give the exact analytic vibrational levels and bond-length change of a diatomic molecule utilizing the Kramers-Henneberger frame which are valid in a wide wavelength range.

F.10 Quantum interference in strong-field ionization by a linearly polarized laser pulse solves the problem of non-zero tunnel exit momentum

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We theoretically and numerically investigate the liberation of an atomic electron by a linearly polarized single-cycle near-infrared laser pulse with a peak intensity corresponding to tunnel ionization. This process is of fundamental importance both in quantum theory and in attosecond science. Several research groups published recent experimental results relevant to tunneling time and nonzero exit momentum of the escaping electron.

Based on a phase space analysis with the Wigner function and by tracking the energy distribution in the instantaneous (Coulomb + laser) potential, we reveal the importance of quantum interference between tunneling and over-the-barrier pathways of escape. We highlight the Wigner function's natural connection to the quantum momentum function (QMF), which enables us to use the QMF as the fundamental quantity to represent the true time-dependent quantum dynamics, including quantum interference. We introduce novel quantum-momentum based initial conditions (QUBIC) by using the suitable value of the QMF as a novel non-zero tunnel exit momentum, without any contradiction to energy conservation, and in a good agreement with recent experimental results.

We give more insight into the onset of the electron's escape process by studying a wave packet which is obtained as the positive momentum and positive energy (PMPE) part of the electron's quantum state at the final instant of the laser pulse. By quantum propagating this PMPE wave packet backwards in time and comparing its Wigner function with classical phase space trajectories, we can demonstrate that the trajectories associated to QUBIC initiate the classical dynamics in excellent agreement with the quantum evolution. Furthermore, these QUBIC trajectories can account for direct ionization and for rescattering, depending on the escape time instant.

Ref.: Hack et al., Phys. Rev. A 104, L031102 (2021)

F.11 High-resolution probing of sub-wavelength confined molecules

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The quantum physics of sub-wavelength confined atomic vapors has been studied with thin-cell spectroscopy, where atoms are confined within the windows of a cell of nanometric thickness comparable to the excitation wavelength. Performing similar experiments with molecular gases is an attractive prospect, of interest for fundamental Casimir-Polder measurements of the molecule-surface interaction and for applications such as compact frequency references. However, high resolution probing of sub-wavelength confined molecules is challenging, due to the small probabilities of molecular transitions, and was so far demonstrated only on a macroscopic cell via selective reflection spectroscopy [1].

Here, we probe molecular gases confined in two different thin-cells (with ZnSe windows) of micrometric thickness. The first cell, of uniform thickness ~ 5.35µm, is used to probe the $\nu 3$ and $\nu 2$ rovibration bands of SF6 and NH3 respectively, around 10.55µm (mid-infrared) as well as the $\nu 1+\nu 3$ band of acetylene at 1.530µm (near-infrared), within the telecommunications wavelength range. The cell thickness corresponds to $\lambda/2$ and $7\lambda/2$ for mid-infrared and near-infrared rovibrations respectively, allowing high resolution (sub-Doppler), linear spectroscopy due to the coherent Dicke narrowing effect [2]. Our experimental spectra are very well reproduced by our theoretical models.

The second cell has a linearly varying thickness from 600-1300nm, allowing us to achieve a stronger confinement and pursue measurements of the molecule-surface Casimir-Polder interaction. Preliminary measurements show that it is possible to probe SF6 and NH3 molecules in the nanometric regime, albeit with a reduced signal amplitude (consistent with the reduction in cell thickness). We are currently examining the possibility of performing thin cell spectroscopy with stronger molecular transitions, such as the HF and OCS vibrations at 2.5µm and 4.85µm respectively.

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F.12 Collision-induced 2^3P-1^1S excitation transfer in helium discharges: assessment and implications for ^{3}He MEOP

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Metastability exchange optical pumping (MEOP) is frequently used to orient the nuclear spin of ^{3}He. It involves optical pumping on the 2^3S-2^3P transition at 1083 nm and transfer of nuclear orientation to the 1^1S ground state by metastability exchange collisions between 1^1S and 2^3S atoms. Systematic investigations of MEOP dynamics in ^{3}He have shown that the current limits in steady-state gas polarisation result from a strong enhancement in angular momentum loss rates due to pump-light absorption [1]. We suggest that collision-induced population transfers in the 2^3P state and excitation transfer between atoms in the 2^3P and 1^1S states mostly contribute to the observed loss of nuclear polarisation. The reported work aims at providing evidence of significant 2^3P-1^1S collisional excitation transfer and at establishing a quantitative link between collisional rate measurements and a pressure-dependent upper limit in ^{3}He polarisation systematically observed above a few millibars [2]. Collisional redistribution of atoms among 2^3P magnetic sublevels was characterized by laser absorption spectroscopy on the 2^3P-3^3S transition at 706.5 nm, using a ladder-type double optical resonance scheme [3]. Clear evidence of excitation transfer was obtained in isotopic ^{3}He-^{4}He mixtures through selective (1083 nm) excitation of one isotope. The recorded spectra were fitted by combinations of narrow Lorentzian and broad Gaussian profiles. Lineshape analyses of various 2^3P-3^3S line components were performed for selected 2^3S-2^3P excitation schemes. They provide access to collision rates related to changes in sublevel and/or level populations, with or without changes in atom velocity. Consistency with an ab-initio-computed cross-section for excitation transfer [4] and with the pressure-dependent MEOP observations[2] will be discussed.

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F.13 Designing potentials with Laguerre-Gaussian modes for systematic effects characterization below 10^{-18} level in strontium optical lattice clocks

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Optical lattice clocks (OLC) have achieved an unprecedented low 10^{-18} frequency uncertainty, being established as a candidate for the redefinition of the second of the international system of units. OLCs have applications ranging from fundamental physics, like dark matter detection, to geophysics and global positioning systems. Currently, the accuracy budget of OLCs is limited by the Black Body Radiation (BBR), cold collisions, and lattice light shift effects. For reducing the impact of these effects, various systems are under consideration by the scientific community, such as cryogenic environments for the interrogation of the atoms to manage the BBR, and 3D optical lattices or tweezers to control the atomic distribution and interactions.
In this working paper, we present recent advances in the development of a third-generation Sr OLC in the

SYRTE at Observatoire de Paris, with a focus on the characterization of BBR, collisional, and density systematic effects below the 10^{-18} level. For realizing this level of accuracy, we have developed a new science chamber made of copper, placed inside a primary vacuum chamber, for reducing the temperature inhomogeneity around the atomic environment below a few 10 mK. In addition, the setup is equipped with an adaptable 1D optical lattice whose transverse profile is shaped using Laguerre-Gaussian (LG_{0l}) modes. This allows for increasing the number of trapping sites while reducing the number of atoms per site. We have locked the internal linear cavity to LG modes with $l = [0, 4]$ meaning trapping depths U_{0l}=[1095E_r, 291E_r, 123E_r, 67E_r, 39E_r] respectively. As a preliminary result, we have trapped atoms in a TEM_{00} lattice; the next stage will be to achieve the trapping of atoms in LG lattices. Finally, we will execute the clock spectroscopy for studying the systematic uncertainties related to BBR, collisional, and lattice light shifts for the implemented LG modes.

F.14 Precision spectroscopy of transitions from the metastable 2 $^3S_1$ state of ^{4}He to high-np Rydberg states

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The metastable He ($(1s)^1(2s)^1$) atom in its singlet (^{1}S) or triplet (^{3}S) states is an ideal system to perform tests of ab-initio calculations of two-electron systems that include quantum-electrodynamics and nuclear finite-size effects. The recent determination of the ionization energy of the metastable $2\,^1$S state of ^{4}He [1] confirmed a discrepancy between the latest theoretical values of the Lamb shifts in low-lying electronic states of triplet helium [2] and the measured $3\,^3\text{D} \leftarrow 2\,^3$S [3] and $3\,^3\text{D} \leftarrow 2\,^3$P [4] transition frequencies and could not be resolved in the latest calculations [5,6]. Currently, we focus on the development of a new experimental method for the determination of the ionization energy of the $2\,^3$S state of ^{4}He via the measurement of transitions from the $2\,^3S_1$ state to np Rydberg states with unprecedented accuracy. Extrapolation of the np series yields the ionization energy with sub-MHz accuracy. We present the progress in the development of our experimental setup, which features a Zeeman decelerator and transverse laser cooling and involves (i) the preparation of a cold, supersonic expansion of helium atoms in the $2\,^3$S state, (ii) the setup and characterization of a laser system for driving the transitions to the np Rydberg states and (iii) the development of a sub-Doppler, background-free detection method. Further, we will provide example spectra of selected $n\text{p}\,^3\text{P}_J \leftarrow 2\,^3S_1$ measurements with a prediction of uncertainties for our final measurement campaign.

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F.15 Comb-assisted Lamb-dip spectroscopy of mercury atoms at 253.7 nm

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We report on saturated absorption spectroscopy of mercury vapors, in coincidence with the $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1$ intercombination transition at 253.7 nm, as performed in a 1-mm long cell at different temperatures, from 283.15 K to 303.15 K. Coherent radiation in the deep-UV region is produced by using a double stage of second harmonic generation in a pair of nonlinear crystals, starting from the near-infrared radiation emitted from an external cavity diode laser (ECDL). The ECDL frequency is tightly locked to the nearest tooth of a self-referenced optical frequency comb synthesizer, whose repetition rate and carrier-to-envelope offset frequency are stabilized against a GPS-disciplined Rb clock. Absolute measurements of the sub-Doppler line-center frequency have been obtained by means of a first-derivative detection method, using a modulation transfer technique. To this purpose, the offset frequency between the ECDL and the comb tooth is dithered by means of a sinusoidal signal, while the comb repetition rate is finely tuned thus allowing us to perform calibrated UV frequency scans across the intercombination line. This system leads to absolute frequency measurements with an overall relative accuracy of a few parts over 10^{11}. Moreover, we present the first high-precision determination of the pressure-broadening coefficient due to Hg-Hg collisions by analyzing the Lamb-dip profile at different values of the mercury vapor pressure. This study is significant for ongoing experiments that employ the mercury intercombination line for temperature metrology as well as tests of fundamental symmetries. Additionally, it holds importance for characterizing interatomic forces and testing the theory of collisional line broadening.

F.16 A comb-locked frequency chain for precision mercury spectroscopy and temperature metrology

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A comb-locked frequency chain was developed for precision laser spectroscopy of mercury vapours at the wavelength of 253.7 nm. The system is based on a double-stage second-harmonic generation process of a near-infrared external-cavity diode laser, acting as pump laser, which is frequency locked to a self-referenced optical frequency comb synthesizer by means of an efficient nonlinear frequency-mixing scheme. An absolute frequency axis in the deep-UV region is produced by scanning the comb repetition rate, with the entire frequency chain following the reference comb tooth. The aim of the work is the construction of a new primary thermometer based upon Doppler width metrology in coincidence with the ^{200}Hg intercombination line. Here we report on the characterization of the phase noise of the deep-UV radiation. The spectral purity of the pump laser is investigated by doing a comparison with an ultranarrow linewidth cw laser source emitting at 1542 nm. The

frequency gap between such laser and the pump laser is bridged by the optical frequency comb, following the method of the direct optical digital synthesis. As a result, the spectral profile of the UV radiation is determined. This is relevant for a careful assessment of the instrumental contribution to the shape of the probed mercury line and, in turn, for the highly accurate retrieval of the Doppler-width. The first spectroscopic measurements of the thermodynamic temperature of the mercury vapours are very promising in view of a low-uncertainty practical realization of the kelvin in the new International System of Units.

F.17 Strontium tweezer arrays for precision measurements

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Arrays of divalent atoms have emerged as powerful platforms for optical atomic clocks, precision measurements, and quantum computation. We have constructed a strontium tweezer array apparatus, towards the implementation of a spin squeezed tweezer array clock using Rydberg-dressing [1]. We produce arbitrary tweezer arrays with a spatial light modulator, creating tweezers at the magic wavelength for the strontium clock transition. Atoms in the array are resolved with 6 micron separations, using a SPAD array detector and a high magnification imaging system. We are now in the process of implementing an optical atomic clock in the tweezer array.

Using Rydberg-dressed interactions in an array of single atoms builds upon previous work in our group. In a single deep tweezer, we demonstrated fast (0.2 ms) number-resolved detection of strontium-88 atoms with 99% single atom fidelity [2]. Imaging fidelity should improve significantly in the magic wavelength array, where atom loss during imaging can be greatly reduced. Interactions between tweezer sites for spin squeezing will be done via Rydberg-dressing, where we previously demonstrated the Rydberg-dressed MOT [3].

The tweezer array also allows an environment for other precision measurements, where the long working distance (37 mm) results in a low field environment. Using atoms from tweezers excited to Rydberg states, we characterised and cancelled the stray electric field at the precise position of the tweezers with our in-vacuo electrodes, reducing the stray field further from 40(2) mV/cm to 2(2) mV/cm. The low field combined with a clock-referenced frequency comb is well suited for improving measurements of strontium Rydberg series, which is important for strontium-based systems and their applications going forwards.

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F.18 High-resolution mid-infrared molecular spectroscopy for precision measurements and tests of fundamental physics

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High spectral resolution molecular spectroscopy has far-reaching applications ranging from astrophysics, remote sensing and Earth sciences to fundamental physics and metrology. Quantum cascade lasers stabilized on optical frequency combs (QCLs/OFC) with traceability to primary frequency standards is a breakthrough technology of this field. It has recently been demonstrated at laboratoire de physique des lasers (LPL) [1]. QCLs/OFC offer an unprecedented level of precision and resolution in the mid-infrared (MIR), the so-called molecular fingerprint region. The need for ultimate frequency control is obvious for fundamental physics such as testing symmetries [2] or measuring fundamental constants and their possible variations in time or space. Those last measurements comparing absorption/emission spectra of cosmic objects and corresponding laboratory values are however limited by the inaccuracy of available laboratory data and further improvements definitely require more accurate laboratory measurements of molecular frequencies. Atmospheric monitoring has also surprisingly a similar requirement of high precision. Remote sensing measurements are often limited by the quality of spectroscopic data.

High precision sub-Doppler spectroscopic techniques in the MIR have so far been limited to very few and relatively simple species. In this talk I will present our latest efforts in order to lift current limitations of QCLs/OFC in terms of spectral coverage and tunability, thus extending frequency metrology methods to an ever increasing number of species, to carry out broadband, sensitive and ultra-precise spectroscopic studies of species of interest for fundamental physics as well as atmospheric studies and astrophysics.

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F.19 Nonlinear pulse compression in a gas-filled multipass cell

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A novel approach is proposed for nonlinear spectral broadening and temporal pulse compression well below the gain-bandwidth limitation of the laser gain medium. We install, in a gas-filled multipass cell, a potassium dihydrogen phosphate (KDP) crystal, which exhibits anomalous dispersion around the central wavelength (1030 nm) of the seed laser. The resulting total dispersion is adjusted by changing the pressure of a normal dispersive gas filling the cell. Chirped mirrors become unnecessary, and pulse compression can be tuned by adjusting the number of passes. Shorter pulses and a broader spectrum will enhance high harmonic generation for an extreme ultraviolet frequency comb which will be employed for quantum logic spectroscopy of highly charged ions. I will present simulation results along with the progress of the assembly of the cell.

F.20 Laser spectroscopy of Iodine molecule in the 14400-14710 cm^{-1} range

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In this work, we report the laser absorption spectroscopy of iodine molecule in the 14400 to 14710 cm^{-1} range. In order to cover this wavelength range, we have used two narrow linewidth diode lasers. One laser was scanned in the 14400 to 14600 cm^{-1} range and another in the 14600 to 14710 cm^{-1} range. Their frequencies were actively measured using a calibrated wavelength meter. The Doppler limited absorption spectroscopy was performed in a 2 m long iodine cell in a double pass configuration at a temperature of 70 °C. Such configuration presents a high signal-to-noise ratio, allowing us to observe a total of 1852 reference lines. For 1278 lines, good agreement is found with the publication by Houssam Salami and Amanda J. Ross (2005) [1], but we have observed 655 new lines due to the high resolution of our laser. The new dataset can be useful as a reference for laser frequency calibration and stabilization.

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F.21 Complete reconstruction of ultrashort laser pulses by convolutional neural networks

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Complete temporal and/or spectral characterization of femtosecond laser pulses can be realized through indirect measurements, like the Frequency Resolved Optical Gating (FROG) [1] technique. FROG records a spectrogram image or trace using the spectrum of the signal created by the superposition of the original pulse and its replica in a non-linear medium, for different delay times between the two pulses. The spectrogram is used to recover the amplitude and phase of the original laser pulse through FROG inversion algorithms. Classical FROG inversion algorithms are based on iterative methods [2-3], therefore may be slower, especially for larger images. Here, we present an alternative way for the retrieval process by making use of the powerful feature extraction capabilities of Convolutional Neural Networks (CNNs) [4], specifically our modified version of the Densenet-BC network [5]. The CNN was trained with computer generated FROG traces (∼100k) and the corresponding spectral electric fields used as labels. The FROG traces are propagated through the neural network, which outputs the predicted spectral field vectors and the training is completed at a small mean absolute error between the original and the predicted fields. The CNN is tested on a separate data set, which never entered the network during training. Our results show a very good reconstruction of the amplitude and phase for simulated traces even with different levels of Gaussian noise added.

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F.22 An efficient Zeeman slower for the ROYMAGE transportable Ytterbium clock

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The frequency of optical lattice clocks (OLCs) based on the narrow ${}^1S_0 \rightarrow {}^3P_0$ transition of $\sim 10^4$ cold atoms trapped in a"magic" optical lattice can now be controlled at the 18-digit level, which makes them the most accurate instruments ever built. Since their frequency depends on the local gravitational potential a 1 m altitude change results in a 10^{-16} frequency variation clocks can contribute to the mapping of the geopotential (chronometric geodesy). In this perspective, SYRTE started in 2021 the development of a transportable ytterbium OLC. In order to fight the inevitable spectral degradation of the laser probing the narrow transition, a possible approach is to lattice-trap atoms as rapidly as feasible.

We present our choice to design a Zeeman slower based on permanent magnets, so as to save electrical power and avoid temperature gradients affecting the clock frequency. We study various configurations, with magnetic field gradients oriented along or perpendicular to the propagation of the atoms, and we discuss the pros and cons. Additionally, preserving a homogeneous light-atoms interaction even a few mm away from the axis is critical to capture more velocity/position classes. To this end, we simulate the joint use of an optical molasses (collimating the flux at the output of the atomic oven), a Zeeman slower and a 2D-MOT (refocusing the flux) to quantify the loading rates that can possibly be achieved. Finally, we present the preliminary results of Zeeman slowing in the apparatus presently being assembled.

Our loading strategy aims at trapping $> 10^4$ atoms in at most a few 10 ms, while preserving a spectroscopy time > 100 ms. This would allow a fractional stability of a few $\frac{10^{-16}}{\sqrt{\tau}}$, with which an integration time $\tau = 1$ day is sufficient to reach a statistical resolution of 10^{-18}. We acknowledge funding from ANR ROYMAGE.The frequency of optical lattice clocks.

F.23 High-resolution spectroscopy of the ground and low-lying excited states of $MgKr^+$ and $MgXe^+$

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Diatomic molecules RgM consisting of a rare-gas atom Rg and an alkaline-earth-metal atom M and their singly and doubly-charged cations RgM^+ and RgM^{2+} have unusual chemical properties related to the low first and second ionization energies of M and the high ionization energy of Rg. The second ionization energy of Mg is lower than the first ionization energy of Ar. Consequently, $MgAr^{2+}$ is thermodynamically stable and Rydberg series of $MgAr^+$ can be observed that converge on the $X^{2+}\ ^1\Sigma^+$ ground state of $MgAr^{2+}$ [1]. In MgKr and MgXe the second ionization energy of Mg is higher than the first ionization energy of the rare gas, and $MgKr^{2+}$ and $MgXe^{2+}$ are predicted to be metastable. We present the results of spectroscopic investigations of $MgKr^+$ and $MgXe^+$ in their ground and low-lying electronically excited states that extend earlier studies of these cations [2,3].

PFI-ZEKE photoelectron spectra of the $X\ ^2\Sigma^+$ ground state were recorded from the $a\ ^3\Pi_0$ metastable state. Spectra of the lowest vibrational levels of $MgKr^+$ and $MgXe^+$ enabled the determination of the adiabatic ionization energy of metastable MgKr and MgXe. Using isolated-core multiphoton Rydberg dissociation (ICMRD) spectroscopy [4] spectra of several electronic states of $MgKr^+$ were observed that are associated with the Rg + $Mg^+(3s/3p)$ dissociation limits. These states are the lowest members of Rydberg series converging on the ground state of $MgKr^{2+}$ and $MgXe^{2+}$.

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F.24 Rovibrational and Hyperfine Structure of the Molecular Hydrogen Ion from Spectroscopy of Rydberg-Stark Manifolds

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Precision measurements of rovibrational energies in H_2^+ provide access to fundamental constants such as the proton-to-electron mass ratio or the proton charge radius, by comparison with theoretical results [1]. Because homonuclear isotopologues of molecular hydrogen are nonpolar, pure rotational and vibrational spectra cannot be measured. Instead, transitions can be driven to Rydberg series converging on different rovibrational states of the ion core [2]. Extrapolation of Rydberg series yields the ionic level energies. We use a combination of precision spectroscopy and calculations of Rydberg-Stark manifolds including electron and nuclear spins to determine rovibrational and hyperfine intervals in H_2^+ and D_2^+ at sub-MHz accuracy.

Precise measurements of core-excited Rydberg states are challenging because of line-broadening effects caused by autoionization. By applying electric fields, states of different values of ℓ are mixed, which increases the non-penetrating character and thus the lifetimes. The high-ℓ states have vanishingly small quantum defects and

form a nearly degenerate Stark manifold. Extrapolation to zero field yields the zero-quantum-defect positions [3], from which the ionization energy can be determined. By applying this method to states with the ion core in different rovibrational states, their relative positions are determined.

We show how Stark manifolds including interactions involving electron and nuclear spins can be accurately calculated with a polarization model for the high-ℓ quantum defects [4] to which spin-orbit, spin-rotation and hyperfine interactions are added.

This contribution focuses on the determination of the fundamental vibrational and the spin-rotation intervals in H_2^+ and the hyperfine splitting in the ground state of D_2^+.

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F.25 Lamb-dip cavity ring-down spectroscopy of acetylene at 1.4 μm

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We report on Lamb dip spectroscopy of weak vibration-rotation transitions of C_2H_2, between 7122 and 7172 cm^{-1}, as performed by means of a comb-assisted frequency-stabilized cavity ring-down spectrometer (CA-FSCRDS). The experimental setup is an upgraded and simplified version of that already developed by our group [1], the main element of novelty being the use of a single extended cavity diode laser tightly locked to a high-finesse cavity and actively referenced to an optical frequency comb.

We measured the frequency of 21 transitions belonging to the P, R, and Q branches of the $\nu_1+\nu_3+\nu_4$ band [1], looking for *ortho* and *para* states of the molecule. Recording sub-Doppler profiles allowed us to determine line center frequencies with high accuracy, the 1-σ overall relative uncertainty being about 3×10^{-11}, on the average. The most important source of uncertainty was the statistical one, which was in the order of $\sim2.8\times10^{-11}$. Our results are three orders of magnitude more accurate than those provided by past FTIR literature as well as those reported in the HITRAN database.

Line pairs of the P and R branches were selected so as to form a Λ-scheme, sharing the exited rotational level. Such a choice made it possible to determine the energy separation of the rotational levels of the ground vibrational state. The retrieved separations agree well with the findings of the Measured Active Rotational-Vibrational Energy Levels (MARVEL) algorithm, thus providing a stringent test of the MARVEL procedure applied to acetylene. Moreover, the level of agreement becomes even higher if energy separations are compared with those that can be determined from the frequencies of the transitions of the $\nu_1+\nu_3$ band at 1.5 μm involving the same rotational levels [2].

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F.26 Coherent Laser Spectroscopy on Potassium D2 Line for Magnetometry Applications

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The coherent magneto-optical resonances (MORs) on the potassium D2 line ($\lambda = 766.7$ nm) are investigated from the point of view of magnetometry applications. The measurements are performed in a cylindrical cell with dimensions (diameter and length) 8 mm and 30 Torr Ne buffer gas. The resonances are registered in Hanle configuration with potassium excited by circularly polarized laser beam (equivalent to two copropagating laser beams with linear polarization), and in a modified Hanle configuration based on counterpropagating pump and probe laser beams with orthogonal linear polarizations. The amplitude, width and contrast of the resonances registered in fluorescence and transmission are compared. The capability of the laser system to work with magnetically unshielded cell is demonstrated. For both geometries, for the temperature interval studied, the registered in transmission MORs are Electromagnetically Induced Absorption (EIA) resonances. When the MORs are registered in fluorescence, at low temperature they are bright. Increasing the cell temperature, the optical thickness of the medium increases. Thus, as a result of radiation trapping, dark resonance with similar contrast and width is observed. There is a temperature range where bright and dark resonances are observed simultaneously. The detuning between their extrema might be used for magnetic field measurement. The registration of bright and/or dark magneto-optical resonances in fluorescence by controlling the optical thickness of potassium vapor by temperature and Light Induced Atomic Desorption (LIAD) is compared. The influence of the laser intensity, buffer gas and transverse magnetic field are considered. The experimental results show the potential of the system for magnetic field sensing and self-calibration.

F.27 The ℓ-dependence of the autoionization rates of core-excited Rydberg states

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Core-excited Rydberg atoms and molecules, in which one electron is excited to a high-lying orbital whereas the residual ion-core is in a low-lying excited state, have proved promising to exploit and manipulate the outstanding properties of the Rydberg electron for, e.g., quantum technology applications. One major hindrance to using these systems is their very short lifetime before spontaneously emitting one electron in a process called

autoionization. We present a theoretical study of the autoionization of core-excited Rydberg states of alkaline-earth-metal atoms for a broad range of n and ℓ values, with the aim to better understand and characterize this process. Alkaline-earth atoms are widely used for Rydberg-atom studies and, because they have only two electrons in their valence shell, extensive and accurate calculations are feasible. We performed large-scale calculations of the autoionization rates of Mg, Ca and Sr using the method of configuration interaction with exterior complex scaling (CI-ECS). CI-ECS allows the treatment of the two-valence-electron dynamics in its full dimensionality and does not rely on the assumptions made in other widely used methods. Diagonalization of the complex-scaled Hamiltonian calculated using numerical basis functions directly provides the autoionization rates of the core-excited Rydberg states, which are twice the imaginary part of the complex eigenvalues. Our calculations were validated by comparison against experimental data available in the literature. We observed and analyzed common trends in autoionization when changing n and, in particular, ℓ, for which we derived physical explanations and empirical laws. The conclusions derived in this work are expected to be general properties of the autoionization process, also applicable to other systems.

F.28 Self-Oscillations in a Strongly-Driven Thermal Vapor with Rydberg Interactions

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Continuously driven, non-linear systems show interesting behaviours such as bistability [1,2] and self-oscillations [3], and have recently come into focus of both theoretical [3,4] and experimental [1,2,5,6] research again. The system's nonlinearity fundamentally changes the response to constant driving and can even facilitate time-periodic solutions such as time-crystals [4]. For three-level EIT in a thermal vapor, with the non-linearity introduced by a Rydberg state, the mechanism inducing bistability in the vapor is currently disputed with candidates being Rydberg-Rydberg interactions [2,7] or Stark shifts induced by plasma formation inside the vapor [5,6]. We report the observation of persistent oscillations in the transmission of a probe laser through a thermal vapor under constant driving. The system is a strongly driven three-level ladder EIT scheme in Rb where we couple the intermediate $5P_{3/2}$ state to a Rydberg state. After an initial bistability arises in the response of the vapor when increasing probe or coupling Rabi frequency, we observe the occurrence of an oscillation regime in the spectrum. When fixing probe and coupling laser detuning within the oscillation regime we find the oscillations to be persistent in time and to show a clear frequency and shape.

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F.29 Performing high precision spectroscopy on ultracold ammonia molecules in an electrostatic trap

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In our setup, ammonia molecules ($^{14}NH_3$) are released vertically, decelerated by a conventional Stark decelerator to 90 m/s and brought to a standstill in a traveling wave decelerator, which holds the molecules near the top. Here, the molecules are cooled down to below 120 microkelvins and subsequently interrogated by microwave or infrared radiation. To avoid Stark shifts by the trapping fields, the trap is turned off and on quickly. In this way, we can investigate molecules in a field-free environment with interrogation times of up to 3 milliseconds.

We present vibrational spectroscopy on the $\nu_1 + \nu_3$ overtone band around 1.5 microns with a precision of 10 kHz, which is a factor of 500 more precise than previous measurements. Using microwave radiation, we show that we can selectively pump away molecules in unwanted hyperfine states. We will discuss future experiments in a molecular fountain to achieve even higher accuracies.

F.30 Current status of the Al^+ ion clock at PTB

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To this day, time is defined via a hyperfine transition in cesium. State of the art cesium clocks reach fractional frequency uncertainties of a few parts in 10^{16} and a statistical uncertainty of the order of $10^{-13}(\tau/s)^{-1/2}$. Higher stability and accuracy can be achieved using optical atomic clocks.

Optical atomic clocks offer atomic transitions with higher clock frequencies. Therefore, they use lasers as local oscillators compared to microwave oscillators in e.g., Cs clocks. Thereby, they can achieve lower statistical uncertainty compared to these clocks.

Here, we present the status of our Al^+ optical ion clock. The advantage of aluminium compared to other clocks species is the verry low sensitivity to external fields. Al^+ exhibits only nuclear Zeeman shifts and a very small blackbody radiation shift. The systematic uncertainty of our setup is estimated to be $1 * 10^{-18}$ using a single Ca^+ ion as a sensor.

Al^+ does not have an accessible transition for laser cooling and detection. Therefore, the Al^+ ion is trapped together with a Ca^+ ion which provides sympathetic cooling of the Al^+/Ca^+ crystal and can be used for state readout using the quantum logic scheme. This scheme, as well as a reduction of the second order Doppler shift requires cooling of the crystal to near the motional ground state. Additionally, we implement an active radio frequency ion trap amplitude stabilization for the Paul trap in order to increase the radial mode frequency stability. Therefore, the uncertainty of an unusually large ac Zeeman shift from the trap radio frequency drive can be decreased.

F.31 Magnetically induced transitions for extension of frequency reference from IR to UV

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A high interest has recently been focused on $F_e - F_g = \pm 2$ atomic transitions of the alkali hyperfine structures. These transitions' probabilities are negligibly small in the absence of a magnetic field; however, they are strongly enhanced when a magnetic field is applied. These transitions are referred to as magnetically induced transitions [1, 2]. We have shown that for ^{87}Rb D_2 line a large frequency shift in the order of several tens of GHz is observed in a magnetic field with the strength of about or larger than 5 kG. As magnetically induced transitions are formed on the highest and the lowest frequency wings of the spectrum and do not overlap with regular transitions, they are of practical interest for mastering new frequency ranges. The key note of this study is the observation of the magnetically induced transitions' shifts in the region of 780 nm-322 nm (infrared-ultraviolet). Nanocell filled with the Rb vapor at half wavelength for $5S_{1/2}$- $nP_{3/2}$ of ^{87}Rb D_2 line transitions, where excited states principal quantum numbers are n = 6,7,8,9, has been used. Application of the nanocell at half wavelength thickness [1], makes it possible to form Doppler free (narrow) atomic transitions for $F_g = 1 \rightarrow F_e = 3$ up to the UV region. The probabilities of all $5S_{1/2}$- $nP_{3/2}$ transitions decrease with the increase of principal quantum number n. In contrast to the probabilities of regular transitions, relative probabilities of the magnetically induced transitions increase. Theoretical calculations match well with available experimental results.

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F.32 PFI-ZEKE characterization of the ground and low-lying excited states of MgO^+

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We report on the characterization of the rovibrational structure of the ground and first excited electronic states of MgO^+ by high-resolution PFI-ZEKE photoelectron spectroscopy. Rotationally cold ($T_{\rm rot} = 5$ K) MgO molecules in the X $^1\Sigma^+$ (v=0-5) levels are generated in a supersonic expansion of a 0.1% N_2O/He carrier gas following laser ablation of a Mg rod [1]. The rovibrational ionization thresholds corresponding to both spin-orbit components ($\Omega = 1/2, 3/2$) of the X^+ $^2\Pi_\Omega$ (v^+=0-10) states and to the lowest vibrational levels of the

$A^+\ ^2\Sigma^+_{1/2}$ state are reached in a resonant $1+1'$ two-photon excitation sequence via the F $^1\Pi$, E $^1\Sigma^+$, and G $^1\Pi$ rovibrational intermediate levels of MgO studied previously by Breckenridge and coworkers [2]. Our new results include accurate values for the first two adiabatic ionization energies of MgO. This work is carried out in the context of our studies of the rovibrational structure of doubly charged dications by high-resolution PFI-ZEKE spectroscopy of singly charged cations as performed recently for $MgAr^{2+}$ [3]. A roadmap towards characterizing the ground state of MgO^{2+} will be discssed. The experiments will reveal whether MgO^{2+} is thermodynamically stable as predicted in Ref. [4] or meastable as predicted in Ref. [5].

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F.33 Investigation of the interplay pumping mechanisms of SiCMOS charge pumps under conditions of elevated temperature and power applied

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Quantum metrology plays a crucial role in modern science and technology, with applications ranging from precision measurements of fundamental constants to quantum information processing. In order to achieve accurate and reliable measurements, a quantum metrology standard requires the use of three electrical quantum effects - the Josephson effect, the quantum Hall effect, and single-electron transport. These effects are used to define the voltage, resistance, and electron charge, respectively, which are in turn used to define the Josephson constant, von Klitzing constant, and electron charge. Among these effects, the single-electron pump is a particularly important device as it allows for the precise and controlled transfer of a single electron. Single-electron pumps have the potential to provide highly accurate and stable current sources, with applications in metrology, quantum computing, and nanoelectronics. As such, the investigation of the pumping mechanism and potential sources of error in Si-CMOS single electron pumps is an important area of research with implications for the development of portable, high-precision current sources for use in quantum metrology and other fields.

Our study focuses on investigating the pumping mechanism in Si-CMOS single electron pumps with a focus on temperatures up to 14K and the influence of AC voltage signal. We analyse the data with the decay-cascade and thermal regime fitting methods to understand the interplay between the two methods. Our findings suggest the transition between these two regimes, and we estimate the accuracy for the pumping mechanism. We propose an ideal temperature regime (a few Kelvins) for operating a SiCMOS charge pump however depend on the AC voltage signal. Our results indicate that this research could lead to the development of a portable charge pump that does not require mK temperatures for operation, offering a scalable electron pump standard.

F.34 Quantum-enhanced multiparameter estimation and compressed sensing of a field

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We show that a significant quantum gain corresponding to squeezed or over-squeezed spin states can be obtained in multi-parameter estimation by measuring the Hadamard coefficients of a 1D or 2D signal. The physical platform we consider consists of two-level atoms in an optical lattice in a squeezed-Mott configuration, or more generally by correlated spins distributed in spatially separated modes. Our protocol requires the possibility to locally flip the spins, but relies on collective measurements. We give examples of applications to scalar or vector field mapping and compressed sensing.

F.35 Sub-Doppler spectroscopy of ^{39}K for magnetic field measurements

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Alkali atoms are commonly used in atomic physics for a number of reasons, the main one being the simplicity of their electronic structure. Relatively cheap lasers are available for the main optical transitions (D lines) of most alkali atoms making them convenient to study experimentally, mainly in the domain of magnetometry. Potassium 39 (^{39}K) is an interesting candidate for such experiments, since it has the smallest characteristic value $B_0 = A_{^2S_{1/2}}/\mu_B \approx 170$ G (where $A_{^2S_{1/2}}$ is the ground state's magnetic dipole interaction constant) characterizing the decoupling of **J** and **I** and therefore the establishment of hyperfine Paschen-Back (HPB) regime. Probing a ^{39}K vapor with a circularly polarized laser while applying a strong enough (> 200 G) magnetic field oriented along the propagation direction of laser allows to record an absorption spectrum in which only 8 spectrally resolved Zeeman transitions (4 for each circular polarization $\sigma^{\pm}$) are visible, while the probabilities of the 16 remaining transitions tend to zero. Complete spectral resolution is obtained thanks to the thickness of the vapor cell (of the order of the transition wavelength), allowing almost complete cancellation of the Doppler broadening. We present a method that allows to measure the magnetic field with micrometer spatial resolution based on the recorded spectra in the range $0.1-10$ kG with a cell of thickness $L = 120\pm5-390\pm5$ nm, which is relevant in particular for the determination of magnetic fields with a large gradient (up to 3 G/μm). The experimental results are verified by theoretical calculations.

F.36 Formation of strongly frequency-shifted EIT resonances using "forbidden" transitions of Cesium

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It is well known that many of the most-used techniques in modern atomic physics were first demonstrated in hot atomic vapors. Nowadays, optical processes occurring in Alkali vapors confined in vapor cells have important applications in various fields, such as optical atomic clocks, atomic magnetometers, atomic gyroscopes, etc. Therefore, the investigation of the peculiarities of atomic transitions of alkali atoms is of utmost importance. Moreover, relatively cheap lasers are available for the main optical transitions (D lines) of most alkali atoms making them convenient to study experimentally, Here, we study the transitions occurring between the Zeeman sublevels of Cesium D_2 line. More precisely, we study the so-called "forbidden" transitions, ie. the transitions satisfying $\Delta F = \pm 2$. One of the most important peculiarities of these transitions is that when applying an external magnetic field, the magnetic-field induced mixing of Zeeman states leads to a significant increase of the transition probabilities. We use for the first time the σ^+ ($\Delta m = +1$) $\Delta F = +2$ transitions of Cesium D_2 line as probe radiation to form EIT resonances in strong magnetic fields (1 - 3 kG), while the coupling is resonant with $F_g = 4 \rightarrow F_e = 5$ transitions. Due to the large frequency shift of the transitions with respect to the external magnetic field, a strong 12 GHz shift was observed making these results useful for potential applications in frequency stabilization. Sufficient spectral resolution is obtained experimentally by probing a Cesium vapor confined in a cell which thickness is of the order of the wavelength of the optical line (852 nm). Preliminary calculations taking into account the geometry of the cell are in reasonable agreement with the experiment.

F.37 Photoelectron Circular Dichroism of fenchone induced by broadband laser pulses

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The angular distributions of photoelectrons which are ionized by circularly polarized light from randomly oriented chiral molecules are asymmetric with respect to the propagation direction of the light [1]. This effect is called Photoelectron Circular Dichroism (PECD) and it was initially predicted in the one-photon ionization, which usually requires circularly polarized ionizing radiation in a frequency range only available at large scale facilities. In 2012, experiments using table-top laser sources demonstrated a PECD between 10% and 20% in the resonance-enhanced multiphoton ionization of fenchone and camphor molecules [2]. The multiphoton ionization regime opens up a possibility for the coherent control of the effect [3]. One possible route to control the multiphoton PECD is to use single broadband laser pulses, which support photons in a large energy interval [4] and can be tailored in their amplitude and phase with pulse-shaping techniques. In this work, the multiphoton PECD induced by coherent broadband pulses with a 1-3 eV energy spectrum is studied theoretically for R(-)-fenchone molecules with different chirps and intensites of the pulses by utilizing the time-dependent single-center method [5]. We observe a stretching (compression) of the positive/negative PECD towards higher (lower) photoelectron energies by going from non-chirped to up-chirped (down-chirped) pulses, and also by going from weak-field to strong-field non-chirped pulses. Our results suggest a possibility to control the sign, size and angular structuring of the multiphoton PECD by single tailored broadband pulses.

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F.38 Progress on a ^{171}Yb active optical clock based on superradiance

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Technical limitations in traditional atomic clocks have opened the doors for new designs and operating schemes to be explored. Among these novel designs, those based on the superradiant emission of atoms have garnered much interest. In particular, the use of narrow-linewidth transitions, such as those in alkaline-earth(-like) atomic systems, allows superradiant pulses to be generated with useful optical power. These pulses can be directly implemented as an ultra-stable frequency reference, thus creating an 'active' optical clock. Nevertheless, the main challenge of these schemes remains obtaining a continuous emission of this signal.

We present our progress on the assembly and operation of an Ytterbium (^{171}Yb)-based active optical atomic clock. Our source is a collimated beam of thermal Yb atoms produced in an oven at 450°C, with natural isotopic abundances, which then passes through a Zeeman slower designed to reduce the velocity of a fraction of the atoms to $\sim$ 10m/s. At this velocity the atoms are within the capture range for a magneto-optical trap (MOT) operating on the 556 nm 1S0→3P1 transition of ^{171}Yb, where the atoms are further slowed. Our current efforts are focused on assembling an optical conveyor belt which will transport the cold atoms to an ultra-stable cavity (targeted fractional frequency stability $\sim 10^{-13}$; finesse $\sim 10^4$). There, the atoms will be excited at 578 nm on the spin- and dipole-forbidden 1S0→3P0 narrow-linewidth (7 mHz) transition in order to generate superradiant emission resulting from the coupling of the atoms to the modes of our cavity. This emission, optimized in the future to be a continuous beam (i.e. a superradiant laser), will serve as a frequency reference for operating our system on the clock transition with a fractional frequency stability that is competitive with that of modern passive optical atomic clocks.

G Atom-like systems

G.1 Laser cooling and shuttling of trapped ions in strongly inhomogeneous magnetic fields

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Magnetic fields are widely used tools for the manipulation of the external as well as the internal degrees of freedom of ions in a wide range of quantum-science experiments. However, in the context of the development of hybrid traps of cold ions and cold neutral molecules, where an ion trap is superimposed with a magnetic trap of molecules to study ion-neutral collisional and chemical processes at very low temperatures, strongly inhomogeneous magnetic fields from the latter can be detrimental for the efficient laser cooling of trapped ions due to position-dependent Zeeman shifts as well as for the shuttling of ions as the intermediate step to form a hybrid trap [1].

Here we demonstrate the efficient laser cooling of Ca^+ ions trapped in a segmented linear Paul trap that is superimposed with an inhomogeneous magnetic field generated by a pair of permanent ring magnets with a field gradient up to 1600 Gauss/mm. We show that by employing two cooling lasers with properly adjusted wavelengths and polarizations and one repumping laser, the trapped ions can be efficiently cooled to a temperature of millikelvin level at different magnetic field strengths and gradients. An efficient shuttling of ions by synchronously varying the ion-trapping electric potentials and laser wavelengths has also been realized with the present setup.

The efficient laser cooling and shuttling of trapped ions in the strongly inhomogeneous magnetic fields have paved the way for studying the cold collisions and reactions between ions and neutral molecules in the hybrid trap which is currently under development in our lab. It also opens more possibilities for manipulating trapped ions using inhomogeneous magnetic fields in quantum-science experiments.

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G.2 Information-theoretical analysis of Dirac and non-relativistic quantum oscillators

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An information-theoretical study of the Dirac oscillator (relativistic) and the quantum harmonic oscillator (non-relativistic) is performed, on the basis of the respective radial densities for a wide range of angular frequencies. In doing so, physically relevant density-functionals are considered, particularly: Shannon-entropy, disequilibrium and Fisher information. These quantities are computed for different quantum states, as characterized by the radial quantum number N, the orbital angular momentum l, and coupling of spin as well. The obtained results are interpreted accordingly with the structural patterns of the respective probability densities.

Firstly it has been distinguished the inclusion or not of a relativistic description within the Hamiltonian of the system. And then, for the relativistic case, both coupling choices among orbital angular momentum and particle spin have been taken into account. In most cases, the closeness between Dirac and Schrödinger solutions strongly depends on the coupling considered, as also occurs with the behavior of the computed functionals for larger/smaller values of the quantum numbers.

Future work is planned for this system, in an information-theoretical framework, by considering (i) the angular dependence of the three-dimensional probability distribution through spherical harmonics, (ii) complexity measures built up as the product of functionals, and (iii) a comparative study by means of similarity and divergence measures, allowing a direct quantitative comparison among different distributions.

G.3 Time Dilation and Relativistic Blueshift in Photoionization of Atoms

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We study the high-intensity multiphoton ionization of Hydrogen by an X-ray frequency laser at relativistic energies, yielding the kinetic energy spectra of the photoelectron, and observe a blue-shift induced by relativistic effects. In the theory of multiphoton ionization of Hydrogen, the effects of relativity and spatial dependence are typically neglected for the sake of computational feasibility, as well as being too small to measure. As advances in high-intensity, short-wavelength lasers are developed, it becomes necessary to investigate the impact of relativistic and/or beyond-dipole corrections, as they are no longer small enough to neglect. Using an ab-initio approach to simulating the ionization process in an exact beyond-dipole treatment using the Dirac equation, we calculate the blueshift of the resonance peaks in the kinetic energy spectrum, obtained from simulations with a 15-cycle pulse of angular frequency 50 atomic units. To explain the shift we model the effects of time dilation on the frequency of the incident laser pulse in the electron's frame of reference during photoionization at relativistic energies, and compare this with the shift found in simulations, finding good agreement between the ab-initio calculations and the simple model.

G.4 Experimental determination of the energy dependence of the rate of the muon transfer reaction from muonic hydrogen to oxygen for collision energies up to 0.1 eV

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We report the first experimental determination of the collision-energy dependence of the muon transfer rate from the ground state of muonic hydrogen to oxygen at near-thermal energies, based on the recent measurements of this transfer rate at temperatures in the range between 70 K and 336 K by the FAMU collaboration. The FAMU experimental data were acquired at thermal equilibrium, and the observable temperature dependence of the transfer rate is related to the Laplace transform of the energy dependence. We resolve the strongly ill-posed inverse problem by combining a set of complementary approaches with established scattering theory results. A sharp increase of the muon transfer rate to oxygen by nearly an order of magnitude in the energy range 0 - 70 meV is found that is not observed in other gases. The results set a reliable reference for quantum-mechanical calculations of low-energy processes with exotic atoms, and provide firm ground for the measurement of the

hyperfine splitting in the ground state of muonic hydrogen and the determination of the Zemach radius of the proton by the FAMU collaboration.

G.5 Electronic Structure of the Rydberg Molecule He-ND_3

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In ultracold configurations of atoms and molecules, Rydberg interactions between atoms and molecules may lead to the formation of ultralong-range Rydberg molecules [1, 2]. These exotic molecules offer an intriguing toolkit for control and manipulation of interatomic and atom-molecule collisions or simulations of chemical reactions, with applications in quantum information processing, many-body quantum physics and ultracold chemistry. In this poster, we consider the ultralong-range Rydberg molecule He-ND_3 and discuss its electronic structure and properties. This molecule is formed when an ammonia-d3 (ND_3) molecule is bound to a long-lived Helium (He) Rydberg atom [3,4]. The interaction of the dipole moment of ND_3 with a He Rydberg atom forms this ultralong-range Rydberg molecule with GHz energies and kilo-Debye permanent electric dipole moments. The adiabatic electronic potentials evolving from the Rydberg states He(ns) and He(np) are deep enough to accommodate vibrational bound states with GHz vibrational spacing, therefore they can be resolved spectroscopically. We also investigate the adiabatic potential curves and the vibrational spectrum for a model system with varying energy splitting and electric dipole moment. Finally, we discuss the effect of an external electric field applied to the Rydberg molecule He-ND_3.

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G.6 Rovibrational dynamics of Rb_2 in a high intensity optical centrifuge

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An optical centrifuge laser pulse consists on a linearly polarised pulse whose polarization axis describes an accelerated circular motion around its propagation axis. It has been shown that this kind of pulses favourishes rotational excitation due to the molecules rotating along them [1]. Taking Rb_2 as a prototype, we investigate the rovibrational dynamics within the electronic state $^3\Sigma$ in the electric field of an optical centrifuge. For the electric field, we consider a time profile similar to the experimental laser pulse used by the group of V. Milner [2], with peak intensities of the order of 10^{11} W/cm^2. For the sake of comparison, we also consider an electric field with constant peak intensity, i.e., without the modulation of the centrifuge, but providing the same amount of energy to the molecule as the centrifuge pulse. For several initial states and peak intensities, we analyze the wave packet dynamics, and show that population is transferred to higher rotational states within the initial vibrational band, to other vibrational bands, and to the continuum, which implies the dissociation of the molecule. We also explore the break down of the rigid rotor approximation, by reducing the peak intensity and searching for the regime where the neighbouring vibrational bands are not populated. For a thermal distribution of molecules, we study the rotational excitation dynamics and observe the adiabatic transfer of rotational population within the lowest vibrational band, whereas for excited vibrational band, this regime is not reached for the considered peak intensities.

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