Cold atoms and molecules for fundamental physics

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Book of Abstracts

OVERVIEW TALKS

Probing fundamental interactions with molecules and atoms

David DeMille, University of Chicago

Precision spectroscopic measurements in molecules and atoms can reveal the presence of new forces and the virtual particles that mediate them. This talk will provide an overview of ongoing experiments of this type. Special emphasis will be given to tests of time-reversal violating phenomena such as electric dipole moments (EDMs) along the spins of quantized systems. EDMs are very well-motivated theoretically, and current experiments in this class are already sensitive enough to probe the existence of particles beyond those in the Standard Model, at scales well in excess of those directly accessible at the Large Hadron Collider. Prospects for dramatic near-future improvements in EDM sensitivity, and the resulting potential for discovery, will be discussed.

Quantum simulation of lattice gauge theories

Marcello Dalmonte, International Centre for Theoretical Physics Trieste

Gauge theories are the cornerstone of our description of nature at the quantum level. At the theoretical level, many of their fascinating aspects - from real time dynamics, to regimes of finite density of baryon matter - represent some of the most notable challenges for computational methods. Over the last decade, this has stimulated a broad effort to understand how to quantum simulate gauge theories on lattices.

In this talk, I will present an overview of the field. Firstly, I will discuss basic motivations, and why simulating gauge theories in AMO systems is fundamentally different than realizing traditional condensed matter models - symmetry engineering vs interaction engineering. Secondly, I will review some early proposals, and contrast them with more modern approaches. Finally, I will present the current experimental state of the art, highlighting challenges and future perspectives.

Atomic Clocks and Search for Fundamental Physics

Tanja Mehlstäubler, Physikalisch-Technische Bundesanstalt

Trapped and laser-cooled atoms and ions allow for a high degree of control of the atomic quantum system. They are the basis for modern atomic clocks, quantum computers and simulators. I will discuss the state-of-the art of modern clock spectroscopy and highlight different approaches such as lattice clocks, single-ion and multi-ion clocks and frequency comparisons to benchmark them. With an aim of reaching a relative accuracy and stability of 10^{-19}, optical clocks open up new applications such as relativistic geodesy and search for dark matter. I will briefly discuss new world-record limits we obtained in our work on an improved test of local Lorentz invariance using $^{172}Yb^+$ ions and the search for new bosons using clock spectroscopy on even Yb^+ isotopes.

Atom Interferometry from Mobile Platforms to Mineshafts: An Overview

Timothy Kovachy, Northwestern University

In this talk, I will introduce the operating principles of atom interferometry and the theoretical framework for understanding how atom interferometers can be used to measure a variety of signals of interest. I will then provide a survey of some of the broadly ranging applications of atom interferometers, including inertial and gravitational sensing, tests of gravity and of quantum mechanics, and measurements of fundamental constants. I will conclude with an overview of the emerging field of long-baseline atom interferometry, including my own work on the MAGIS-100 100-meter-tall atom interferometer under construction at Fermi National Accelerator Laboratory, and discuss how these atom interferometers will pursue scientific goals including dark matter searches and gravitational wave detection.

INVITED TALKS

Searching for a fifth fundamental force using isotope-shift spectroscopy of trapped calcium ions

Diana Craik, ETH Zurich

Isotope shift (IS) spectroscopy of atoms and ions has been proposed as a method to search for a fifth fundamental force. This hypothetical force acts between neutrons and electrons and is mediated by a dark-matter-candidate boson in the intermediate mass range (100eV to 10MeV). The existence of this new force would cause neutron-number-dependent (and hence, isotope dependent) shifts in atomic transition frequencies. To distinguish these shifts from Standard Model

(SM) shifts (produced by, for example, changes in the Coulomb potential due to differences in nuclear charge distribution between isotopes), one measures isotopes shifts on at least two transitions between three or more distinct pairs of isotopes. The data can then be plotted on a "King plot", which displays a nonlinearity if physics beyond first-order SM effects has contributed to the measured isotope shifts.

Using an entanglement-enhanced technique to reject common-mode noise, we measure isotope shifts on the 729-nm electric quadrupole transition between pairs of co-trapped calcium ions at 100mHz precision, two orders of magnitude below the previous best measurement. We combine our measurements with IS measurements made by the group of Piet Schmidt on the 570nm transition in Ca14+, and improved nuclear mass measurements made by the group of Klaus Blaum, to produce the first sub-Hz King plot.

King plots in calcium had previously remained linear up to the 10Hz level -- our improved precision now reveals a large King non-linearity.

Whilst the second-order mass shift is an expected SM source of nonlinearity, a decomposition analysis of the nonlinearity pattern we observe reveals evidence for at least one other contributing source. In this talk I will discuss the implications of our results both to our understanding of nuclear structure and to the search for new physics.

Isotopologue-selective laser cooling of barium monofluoride molecules

Tim Langen, TU Wien

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

Cold-atom analogues for vacuum decay

Alex Jenkins, University College London

False vacuum decay plays a pivotal role in many models of particle physics and the early Universe. However, we lack a satisfying theoretical understanding of this process, with existing approaches working only in imaginary (Euclidean) time, and relying on assumptions that have yet to be empirically tested. A promising route forward is to use cold-atom systems which undergo first-order phase transitions that are analogous to vacuum decay. In this talk, I will present recent theoretical work to understand this analogy using semiclassical lattice simulations, and will discuss possibilities and challenges for realising these analogues in the laboratory.

False vacuum decay via bubble formation in ferromagnetic superfluids

Gabriele Ferrari, University of Trento

Metastability stems from the finite lifetime of a state when a lower-energy configuration is available but only by tunneling through an energy barrier. In classical many-body systems, metastability naturally emerges in a first-order phase transition and a prototypical example is a supercooled vapor. The extension to quantum field theory and quantum many-body systems has attracted significant interest in the context of statistical physics, protein folding, and cosmology, for which thermal and quantum fluctuations are expected to trigger the transition from the metastable state (false vacuum) to the ground state (true vacuum) through the probabilistic nucleation of bubbles. However, the theoretical progress in estimating the relaxation rate of the metastable field through bubble nucleation has yet to be validated experimentally. Here, we experimentally observe bubble nucleation in isolated and coherently coupled atomic superfluids, and we support our observations with numerical simulations.

Searching for variations in fundamental constants with an optical clock

Rachel Godun, National Physical Laboratory

One of the optical clocks operated at the UK's National Physical Laboratory is based on a single ion of ytterbium, held in an rf Paul trap. The 467-nm electric octupole (E3) transition in the ytterbium ion makes a good clock reference because it has an extremely narrow linewidth and also relatively low frequency shifts in the presence of external electric and magnetic fields. Furthermore, the E3 transition in $^{171}Yb^{+}$ is also particularly sensitive to changes in the fine structure constant, which if observed would indicate physics beyond the Standard Model. In this talk, I will show how the extraordinary accuracy and stability of the measured Yb^{+} clock frequency is enabling it to be used as a precision sensor, searching for changes in the fundamental constants.

Even the absence of any visible changes in the constants provides useful information as it allows constraints to be placed on multiple theories of fundamental physics.

Searching for new physics on a tabletop with a miniature network of optical atomic clocks

Shimon Kolkowitz, University of California Berkeley

The remarkable precision of optical atomic clocks offers sensitivity to new and exotic physics through tests of relativity, searches for dark matter, gravitational wave detection, and probes for beyond Standard Model particles. To this end, we have recently realized a "multiplexed" strontium optical lattice clock consisting of two or more clocks in one vacuum chamber, forming a miniature clock network. This enables us to bypass the primary limitations of typical atomic clock comparisons and to achieve measurements with greater than 19 digits of both precision and accuracy. In this talk I will explain the motivation, concept, and operating principles of our multiplexed optical lattice clock. I will then present recent experimental results in which we performed a novel, blinded, precision test of the gravitational redshift with a vertical array of 5 evenly-spaced ensembles of ultra-cold strontium atoms spanning a total height difference of 1 cm. I will present the error budget produced from our systematic evaluation, and the unblinded results of our first test. I will explain how these results can also be viewed as proof-of-principle measurements of relativistic gravitational potential differences at the millimeter scale, with applications to geodesy. Finally, I will discuss the outlook for using our apparatus for future searches for new physics, including a novel direct test of the Einstein Equivalence Principle, and explorations of the interplay between general relativity and quantum mechanics.

Dark matter searches with atom interferometry

Chris McCabe, King’s College London

Atom interferometry is poised to make significant contributions to fundamental physics, particularly in the search for ultra-light dark matter and gravitational waves [1]. This progress is driven by the development of large-scale terrestrial instruments and the promise of forthcoming space-based missions. We explore both the short-term and long-term potential of these instruments, addressing selected challenges such as noise mitigation strategies [2,3] and methods for accurately reconstructing dark matter parameters [4].

[1] Badurina et al, JCAP 05 (2020) 011
[2] Badurina et al, Phys.Rev.D 107 (2023) 5, 055002
[3] Carlton et al, Phys.Rev.D 108 (2023) 12, 123004
[4] Badurina et al, Phys.Rev.D 108 (2023) 8, 083016

Gravitational effects in atom interferometry

Chris Overstreet, Johns Hopkins University

The high sensitivity of light-pulse atom interferometry, which uses lasers to separate and interfere atomic wave packets, makes it particularly well-suited for gravitational measurements. In this talk, I will discuss three experiments performed with the 10 meter atom interferometer at Stanford: a test of the equivalence principle, an observation of a quantum system in curved spacetime, and a measurement of a gravitational Aharonov-Bohm effect. I will also describe prospects for improved tests of gravity in next-generation experiments.

Multi-photon Clock Atom Interferometry

Jan Rudolph, Stanford University

Narrow clock transitions in alkaline-earth-like atoms serve as the foundation for the world's best atomic clocks and for long-baseline atom interferometer concepts in gravitational wave detection. Such transitions naturally occur in fermions but are strongly forbidden in bosons. We demonstrate a coherent three-photon clock transition in bosonic ^{88}Sr and realize a proof-of-principle multi-photon clock atom interferometer. This technique unlocks bosonic isotopes for next-generation quantum sensors like MAGIS-100.

CONTRIBUTED TALKS

Trapping SrOH for Measurements of Fundamental Physics

Annika Lunstad, Harvard University

Laser-coolable polyatomic molecules containing heavy nuclei have great potential as tools for probing fundamental physics, such as being used to search for the electron electric dipole moment (eEDM). These benefits are largely due to the many degrees of freedom that a complex molecule possesses; however, this structure also makes cooling and trapping the molecules difficult. To date, only one other polyatomic molecule, CaOH, has been laser-cooled and trapped in a magneto-optical trap (MOT). SrOH, which has many of the same characteristics that made it possible to laser-cool CaOH [1, 2] also has sensitivity to Beyond the Standard Model physics. To that end, we here report a MOT of SrOH containing 10^3 molecules. We will also discuss our next steps towards a precision measurement using SrOH, including finding further vibrational repumpers, sub-Doppler cooling, and loading into an ODT.

[1]: Kozyryev et al., PRL, 2017
[2]: Lasner et al., PRA, 2022

An experiment to measure the electron's electric dipole moment using an ultracold beam of YbF molecules

Freddie Collings, Imperial College London

The Standard Model predicts that the electron's electric dipole moment (de) is too small to measure with current technology [1]. However, theories that extend the Standard Model predict much larger values, often exceeding 10^{-29} e cm. With the current experimental upper limit set at $|de|<4.1\text{x}10^{-30}$ e cm [2], we can expect that improved measurements will either discover new physics or rule out most of the remaining parameter space for popular theories beyond the Standard Model. Measurements of de are made by measuring the precession of the electron spin induced by an applied electric field. The precession angle is enhanced when the electron is bound to a heavy polar molecule. The precision can be further improved by increasing the spin precession time and the total number of molecules detected. Therefore, to achieve high precision, we have produced an intense beam of laser-cooled YbF molecules [3] and built an experiment to measure de using this beam [4]. The laser cooling increases the beam brightness by at least a factor 300, leading to a projected shot noise statistical sensitivity better than 10^{-30} e cm. Realising such high precision requires a spin precession region with exceptionally low magnetic noise. Our apparatus features ceramic electric field plates inside a glass vacuum chamber, minimising magnetic Johnson noise, a four-layer magnetic shield with a shielding factor exceeding 10^6, and an array of atomic magnetometers which measure the magnetic noise in our experiment to be below 50 fT/√Hz at 1 Hz. I will present our recent progress in characterising the noise in this apparatus and progress in creating spin interferometer fringes to measure de.

[1] M. Pospelov and A. Ritz, CKM benchmarks for electron electric dipole moment experiments, Phys. Rev. D 89, 056006 (2014).
[2] T. S. Roussy et al., An improved bound on the electron's electric dipole moment., Science 381, 46 (2023).
[3] X. Alauze et al., An ultracold molecular beam for testing fundamental physics, Quantum Sci. Technol. 6, 044005 (2021).
[4] N. J. Fitch et al., Methods for measuring the electron's electric dipole moment using ultracold YbF molecules, Quantum Sci. Technol., 6, 014006, (2021).

Precision measurements in the mid-infrared with cold molecules

Marylise Saffre, Laboratoire de Physique des Lasers

Precision measurements with molecular systems offer numerous exciting prospects, including measuring fundamental constants and their temporal variation, testing fundamental symmetries, interpreting congested astrophysical spectra, and modelling our atmosphere. We will report on our efforts to develop a new setup for high-precision mid-infrared absorption spectroscopy of increasingly complex polyatomic molecules in the gas phase [1]. This setup aims to resolve individual rovibrational lines and measure their frequencies at metrological precisions. At room temperature, complex polyatomic molecules tend to have crowded rovibrational spectra. To simplify these spectra and obtain reasonable absorption signal, it is necessary to cool the molecules of interest, introducing them in a cryogenic cell where they are thermalised by collisions with a cold buffer gas.

To perform high-resolution spectroscopy, we have also developed an ultra-stable and frequency-controlled mid-infrared quantum cascade laser (QCL) around 10 µm calibrated to some of the world's best frequency standards. We will present our recent results using this stable and accurate mid-infrared source to study various complex molecular species of fundamental, atmospheric and astrophysical interest such as methanol, ammonia or trioxane, with record kHz uncertainties on line positions.

The combination of these two developments opens up possibilities in fundamental physics. For example, I will present our recent efforts to measure the tiny energy difference between two enantiomers of organometallic chiral species [1], such as chiral methyltrioxorhenium derivatives [3] and ruthenium(III) acetylacetonate [4]. This energy difference is a signature of parity-violation symmetry, predicted to be induced by electroweak interactions, and a sensitive probe of dark matter. These developments also allow ultra-precise spectroscopic measurements to be improved and molecular databases to be filled with increasingly accurate parameters for even more complex polyatomic molecules of astrophysical and atmospheric interest, such as PAHs [5].

[1] A Cournol et al, Quantum Electron. 49, 288 (2019).
[2] SK Tokunaga et al, New J. Phys. 19, 053006 (2017); P Asselin et al, Phys. Chem. Chem. Phys 19, 4576 (2017).
[3] ES Gauthier et al, Angew. Chem. Int. Ed. 59, 8394 (2020); N Saleh et al, Chirality 30, 147 (2018).

[4] MR Fiechter et al, J. Phys. Chem. Lett. 13, 10011 (2022); B Darquié et al, Phys. Chem. Chem. Phys. 23, 24140 (2021).
[5] PB Changala et al, Science. 363, 6422 (2019).

Testing fundamental physics with molecular lattice clocks

Mateusz Borkowski, University of Amsterdam

Molecular lattice clocks promise measurements of molecular transition frequencies at unprecedented precision and accuracy. On the example of the vibrational strontium dimer clock I will show how a molecular lattice clock can be implemented and characterized [1, 2]. Then, I will present how vibrational [1] and optical [3] molecular lattice clocks could be used to place new limits on non-Newtonian gravitylike interactions [4, 5], test effects beyond the Born-Oppenheimer approximation [6] and track the variations of fundamental constants [7].

[1] K. H. Leung, B. Iritani, E. Tiberi, I. Majewska, M. Borkowski, R. Moszynski, and T. Zelevinsky, `Terahertz Vibrational Molecular Clock with Systematic Uncertainty at the 10^{-14} Level,' Phys. Rev. X 13, 011047 (2023).
[2] B. Iritani, E. Tiberi, W. Skomorowski, R. Moszynski, M. Borkowski, and T. Zelevinsky, `Accurate Determination of Blackbody Radiation Shifts in a Strontium Molecular Lattice Clock,' Phys. Rev. Lett. 131, 263201 (2023).
[3] M. Borkowski, `Optical lattice clocks with weakly bound molecules,' Phys. Rev. Lett. 120, 083202 (2018).
[4] M. Borkowski, A. A. Buchachenko, R. Ciuryło, P. S. Julienne, H. Yamada, Y. Kikuchi, Y. Takasu, and Y. Takahashi, `Weakly bound molecules as sensors of new gravitylike forces,' Sci. Rep. 9, 14807 (2019).
[5] E. Tiberi, M. Borkowski, B. Iritani, R. Moszynski, T. Zelevinsky, `Searching for New Fundamental Interactions via Isotopic Shifts in Molecular Lattice Clocks,' arXiv:2403.07097 (2024).
[6] M. Borkowski, A. A. Buchachenko, R. Ciuryło, P. S. Julienne, H. Yamada, Y. Kikuchi, K. Takahashi, Y. Takasu, Y. Takahashi, `Beyond-Born-Oppenheimer effects in sub-kHz-precision photoassociation spectroscopy of ytterbium atoms,' Phys. Rev. A 96, 063405 (2017).
[7] M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson Kimball, A. Derevianko, and Charles W. Clark, `Search for new physics with atoms and molecules,' Rev. Mod. Phys. 90, 025008 (2018).

Hydrogen lattice clocks, isotope shift spectroscopy and bounds on physics beyond the standard model

Robert Potvliege, Durham University

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We consider the use of hydrogen and deuterium spectroscopy in the search of physics beyond the standard model and the potential use of optical traps in this context. Specifically we consider the wide class of models that can be described by an effective Yukawa-type interaction between the nucleus and the electron (or the muon for the muonic species). We find that it is possible to set bounds on new light-mass bosons that are orders of magnitude more sensitive than those set using a single isotope only provided the interaction couples differently to the deuteron and proton. Further enhancements of these bounds by an order of magnitude or more would be made possible by extending the current set of data to measurements of a transition between the 2s state and a Rydberg s-state with an experimental error of 100 Hz or better [1]. In terms of prospects for achieving this, we find that a hydrogen optical lattice clock could operate with an intrinsic linewidth of the order of 1 kHz, which would provide an independent measurement of the 1s-2s interval free from motional systematics, and that trap induced losses do not limit measurements on other transitions [2].

[1] R M Potvliege, A Nicolson, M P A Jones and M Spannowsky, Phys. Rev. 108, 052825 (2023)
[2] J P Scott, R M Potvliege, D Carty and M P A Jones, Metrologia 61, 025001 (2024)

CeNTREX: A Search for Time Reversal Symmetry Violation using 205TlF molecules

Olivier Grasdijk, Argonne National Laboratory

The Cold molecule Nuclear Time-Reversal EXperiment (CeNTREX) aims to search for the fundamental time-reversal symmetry (T) and parity (P) violation in the hadronic sector. The Standard Model provides for T (and hence CP) symmetry violation in the quark mixing (CKM) matrix, but this is not sufficient to generate the magnitude of the baryon asymmetry observed in the universe. Many Standard Model extensions propose additional sources of T-violation, and Schiff moments and electric dipole moments (EDMs) are excellent probes free of Standard Model backgrounds. CeNTREX utilizes shifts in nuclear magnetic resonance frequencies of the 205Tl nucleus in highly polarized thallium fluoride (TlF) molecules to search for these T violating interactions. With the expected experimental sensitivity, we would be able to set competitive bounds on θQCD, quark chromo electric dipole moments (cEDMs), and the proton EDM. CeNTREX uses modern methods including a cryogenic molecular beam source, optical state preparation and detection, and coherent quantum state manipulation. This poster provides an overview of the experiment and the techniques involved, its current status and recent progress, as well as the upcoming developments and anticipated timeline for a nuclear Schiff moment measurement.

Nuclear Interferometry for Ultra-Light Dark Matter Detection

Hannah Banks, University of Cambridge

We propose the nuclear interferometer - a single photon interferometry experiment based upon the Thorium-229 nuclear clock transition - as a novel detector for ultra-light dark matter (ULDM). Thanks to the enhanced sensitivity of this transition to the variation of fundamental constants we find that possible realisations of such an experiment deploying either single ions or clouds of atoms have the potential to be competitive with advanced very long-baseline terrestrial clock atom interferometers in the search for ultra-light dark matter with scalar couplings to photons. Nuclear interferometry would also offer an unparalleled window to new physics coupling to the QCD sector via quarks or gluons, with a discovery reach potentially exceeding existing and proposed experiments over a range of frequencies. Such a search would complement nuclear-atomic optical clock frequency comparisons, moving in the direction of well-motivated parameter space.

A recoil measurement scheme in intermediate-scale atom interferometers for determining fundamental constants

Jesse Schelfhout, University of Oxford

Atom-interferometric recoil measurements currently limit the precision of many of the fundamental constants, including the fine-structure constant, the atomic mass constant (and hence the masses in kilograms of many particles), the vacuum magnetic permeability and electric permittivity, the Bohr magneton and the Bohr radius [1]. Very-long-baseline atom interferometry (of order 100m-1km) presents an interesting science case for gravitational wave detection and dark matter investigations. Intermediate-scale instruments (of order 10m) are under development as technology pathfinders, bridging the gap between laboratory-scale and very-long-baseline instruments. We have devised a scheme for photon-recoil measurement in these intermediate-scale atom interferometers [2], whereby the recoil phase can be optimised through strategic use of large momentum transfer and the gravity gradient phase can be mitigated by crossing the spatial trajectories of two Ramsey-Bordé interferometers. We find that, using existing atom interferometry techniques, our scheme implemented in a 10-metre instrument operating on the clock transition in Sr or Yb is more than sufficient to increase the precision of the fine-structure constant by an order of magnitude. These measurements find application in testing the Standard Model of particle physics to the highest precision using the magnetic moment of the electron [3].

[1] E. Tiesinga, P. J. Mohr, D. B. Newell, and B. N. Taylor (2024), "The 2022 CODATA Recommended Values of the Fundamental Physical Constants" (Web Version 9.0). Database developed by J. Baker, M. Douma, and S. Kotochigova. Available at https://physics.nist.gov/constants.
[2] J. S. Schelfhout, T. M. Hird, K. M. Hughes, and C. J. Foot, arXiv:2403.10225 [physics.atom-ph].
[3] X. Fan, T. G. Myers, B. A. D. Sukra, and G. Gabrielse, Phys. Rev. Lett. 130, 071801 (2023).

Progress towards a new molecular lattice clock to search for time variation of the proton-to-electron mass ratio

Jonas Rodewald, Imperial College London

The search for time-variation of fundamental constant is a promising way to probe physics beyond the standard model. In the frame of the QSNET project, we are setting up a molecular lattice clock to test for time-variation of the proton-to-electron mass ratio. The clock will be based on the fundamental vibrational transition in Calcium Monofluoride (aF) at a wavelength of around 17μm. The transition is expected to have a few-Hz linewidth and be largely insensitive to systematic DC Stark or Zeeman shifts. Additionally, the AC Stark shifts of the ground and excited states of the clock transition are expected to cancel for several wavelengths, potentially facilitating the trapping of the molecules in a magic wavelength lattice. While in our lab we can already trap sufficient numbers of CaF molecules in a 1D optical lattice at low temperatures, we are currently constructing a Raman laser system to drive the clock transition with long coherence times. We have located the clock transition by driving it with a 17μm Quantum cascade laser while simultaneously performing FM spectroscopy of known N2O absorption lines. In the future we plan to reference the CaF lattice clock to a Sr lattice clock via an optical frequency comb and establish a new frequency standard in the MID IR.

Precision monitoring of classical and quantum fluid interfaces for gravity simulators using optical sensors

Sreelekshmi Ajithkumar, University of Nottingham

In classical and quantum fluids, their interfacial wave dynamics can be used to simulate gravitational effects and early universe scenarios. Investigating interface waves using fluid surface profilometry has become an essential tool in these analogue gravity experiments using fluids at room and low temperatures. We use different local and global optical detectors for mapping the interface profile, employing optical metrology techniques, such as digital holography, spectroscopy, and interferometry, which offer optimal precision and resolution. Here, we present sensors for monitoring classical and quantum fluid interfaces. While our global detection scheme employs multiplexed digital holography to retrieve real-time reconstructions of a sample's 3D profile, the local detector uses spectroscopy and interferometry to capture the temporal evolution of the modes existing in the system. The main investigations conducted so far with these sensors include fluid depth monitoring, evaporation rate, and thermal fluctuation studies. All the detection methods presented here are realised with an extended vision to be incorporated into experimental simulators for gravity and the early universe in superfluid Helium. Other than fluids, some of these methods have the potential to be implemented on a broad range of transparent media.

Towards quantum simulation with random, all-to-all interacting Fermions

Francesca Orsi, Ecole Polytechnique Fédérale de Lausanne

Holographic duality provides connection between certain quantum many-body physics models and general relativity. A hallmark example of such a model is the SYK model, describing fermions with all-to-all, random interactions. A recent proposal shows how this model could be simulated on a cavity QED platform, provided careful engineering of the randomness of the interactions mediated by the cavity.

I will report on our progresses towards an experimental implementation of the SYK model using cold fermionic atoms in a high-finesse cavity.

I will explain how we built and operated a cavity-microscope device allowing for spatio-temporal programming of the light-matter coupling of atoms in a high finesse cavity, and how we can controllably introduce randomness in the cavity-mediated interactions between atoms trapped in the same cavity field. These two achievements combined pave the way to an analogue simulation of all-to-all random, programmable interactions between fermions.

Precision spectroscopy of the 2S-6P transition in hydrogen and deuterium

Vitaly Wirthl, MPQ

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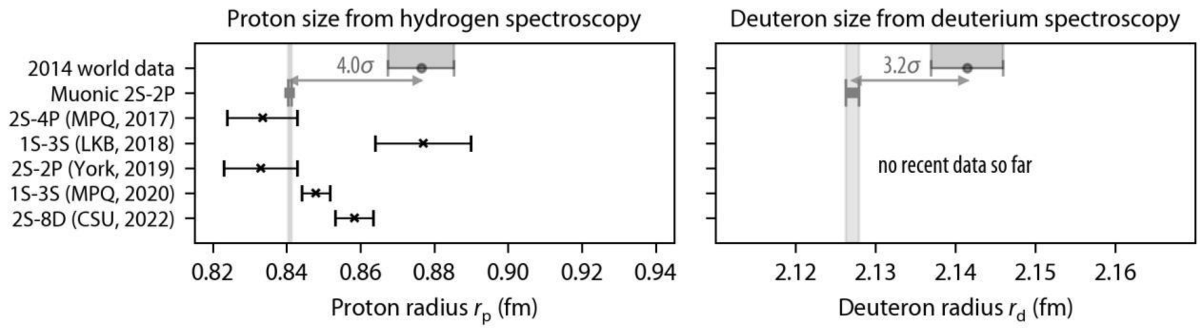
Both atomic hydrogen and deuterium can be used to determine physical constants and to test bound-state Quantum Electrodynamics (QED). By combining at least two transition frequency measurements in each isotope, the proton and deuteron radii, along with the Rydberg constant, can be determined independently [1]. This is particularly interesting because of the tensions within the recent hydrogen measurements, which leaves room to speculate about possible new physics [2], as well as because no recent deuterium measurements are available such that a discrepancy with muonic deuterium persists [3]:



Using our improved active fiber-based retroreflector to suppress the Doppler shift [4], we recently measured the 2S-6P transition in hydrogen with a relative uncertainty below one part in 1012, allowing one of the most stringent tests of bound-state QED. Here, we report on the status of the ongoing analysis. We also performed a preliminary measurement of the same transition in deuterium. In contrast to hydrogen, the 2S-6P measurement in deuterium is complicated by the simultaneous excitation of unresolved hyperfine components, possibly leading to quantum interference between unresolved lines [5]. Our detailed study of these and other effects in deuterium demonstrates the feasibility of determining the 2S-6P transition frequency with a similar precision as for hydrogen.

[1] R. Pohl et al., Metrologia **54**, L1 (2017)

[2] A. Brandt et al., Phys. Rev. Lett **128**, 023001 (2022)

[3] R. Pohl et al., Science **353**, 669–673 (2016)

[4] V. Wirthl et al., Opt. Express **29**(5), 7024-7048 (2021)

[5] Th. Udem et al., Ann. Phys. **531**, 1900044 (2019)

POSTERS

Parity-violation effects in the nuclear spin-rotation and NMR shielding tensors of tetrahedral molecules

Ignacio Agustín Aucar, University of Groningen

We present a four-component relativistic study of nuclear spin-dependent parity-violation (PV) effects due to electroweak interactions in nuclear spin-rotation (NSR) and NMR shielding tensors. Our calculations allow planning and interpreting possible future experiments aimed at giving a strict probe of the Standard Model of particle physics, based on the observation of PV effects on molecular parameters. An exploratory application of this theory to a set of chiral molecules reveals the crucial importance of including relativistic and correlation effects to adequately describe these parameters. It is observed that in the molecules containing both H and F atoms, the PV effects are enhanced in the PV-NSR and PV-NMR-shielding constants.

Quantum sensing with ultracold atoms in optical lattices

Vineet Bharti, University of Bristol, United Kingdom

We are developing a multi-axis quantum inertial sensor with ultracold atoms using a shaken lattice interferometry protocol [1-3]. In our experiment, the atoms will be trapped in a three dimensional (3D) optical lattice. The optical lattice will be phase modulated to split, propagate and recombine the trapped atoms. The 3D shaken optical lattice will serve as a quantum sensor that can measure the accelerations and rotations applied to the system, along all three Cartesian axes. In my presentation, I will give the overview of our quantum sensor and discuss the ongoing progress of the experiment.

[1] C. A. Weidner, H. Yu, R. Kosloff and D. Z. Anderson, Phys. Rev. A 95, 043624 (2017).
[2] C. A. Weidner and D. Z. Anderson, Phys. Rev. Lett. 120, 263201 (2018).
[3] C. A. Weidner and D. Z. Anderson, New J. Phys. 20, 075007 (2018).

ZOMBIES: Towards measuring the parity-violating nuclear anapole moment of 137Ba in BaF molecules

Mangesh Bhattarai, University of Chicago

We describe progress towards measuring the parity-violating nuclear anapole moment of 137Ba in barium monofluoride (BaF) molecules. We present our measurement scheme and discuss a proof of principle experiment with the 19F nucleus in 138Ba19F. A sensitivity sufficient to measure the predicted effect in 137BaF, at the 10% level, was achieved. We have since incorporated several improvements into our system, such as a cryogenic buffer gas beam source and an improved laser frequency locking scheme. The A 2Π1/2 and D 2Σ+ states of BaF are used for the quantum state preparation and detection needed to measure the anapole moment in 137Ba. We present recent measurements of the hyperfine splittings of the A 2Π1/2 state, and progress towards further spectroscopy of both this state and the D 2Σ+ state. We also sketch new strategies to increase the flux of the low-abundance isotopologue 137BaF in our experiment.

The NL-eEDM project

Hendrick Bethlem, Vrije Universiteit Amsterdam

The NL-eEDM consortium aims to measure the electric dipole moment of the electron using a laser-cooled, Stark decelerated beam of barium fluoride molecules. I will give an update of the status of the project.

Direct laser cooling of He_2^*

Max Beyer, VU Amsterdam

Laser cooling of atoms has revolutionized physics and allowed studying nature with unprecedented sensitivity, precision, and accuracy. With their additional degrees of freedom, ultracold molecules offer even more.

I will discuss direct laser cooling of the lightest and first homonuclear molecule He_2^*. The light mass of the molecule, absence of hyperfine structure, and a restricted set of rotational states due to the Pauli principle, drastically reduce the level density and facilitate laser and evaporative cooling.

The triplet helium dimer can be categorized as a Rydberg Molecule. The Rydberg electron doesn't contribute significantly to the chemical bond in Rydberg molecules, resulting in diagonal Franck-Condon factors of electronic transitions and making them suitable for laser cooling. Three laser cooling transitions - in the UV, NIR and IR - were identified in He_2^*.

This project aims to provide a controllable, simple 4-electron system at record low temperature, allowing quantum sensing and precision measurements to test quantum physics and the quantum, nature of collisions with unprecedented accuracy - while being accessible to highly accurate ab initio computational methods.

Applications involve a measurement of the atomic polarizability of He ground-state atoms, being accessed via the long-range part of the molecular potential of He_2^+. Using Rydberg series extrapolation, intervals between excited vibrational levels in the cation, which are particularly sensitive to the static polarizability, are measured. Accurate measuring methods for the polarizability of helium and other rare gases are of utmost importance for paving the way for new quantum pressure standards, which became possible after establishing the new international system of units (SI) in 2018. The pressure is related via the gas law to the particle density, which can be measured via monitoring a change in the dielectric constant of a capacitor or the refractive index of light inside a cavity - if an accurate polarizability is known.

Experimental Realization of a Two-Component Sodium Potassium Mixture

Brian Bostwick, University Heidelberg

Dual-species Bose-Einstein condensates (BEC) provide a versatile platform for many-body quantum dynamics research. Using degenerate mixtures of sodium and potassium, we utilize the substantial inter-species and intra-species of Feshbach resonances to investigate quantum simulation and mixture dynamics.

Atom interferometer searches for spin-2 ultra-light dark matter

John Carlton, King's College London

Atom interferometers are a new class of quantum sensors capable of making precision measurements in many areas of fundamental physics including gravitational wave and ultra-light dark matter (ULDM) searches. While the sensitivity of atom interferometers to scalar ULDM has been established [arXiv: 1911.11755; arXiv: 2308.10731], spin-2 ULDM models are also well motivated but have yet to be fully explored. In this talk I will outline the phenomenology of spin-2 ULDM in atom interferometers and discuss how best to optimise searches by operating multiple experiments in a network. Existing laser interferometer searches for spin-2 ULDM will be complemented by atom interferometers by probing different mass parameter space and offering a distinct method of detection. Not only will spin-2 ULDM induce a change in the laser phase measured in the interferometer but will additionally couple directly to the internal energy states of the atoms. Atom interferometers are uniquely sensitive to both effects, which will enhance the limits these experiments will place on spin-2 ULDM and help distinguish these signals from scalar candidates. Work in collaboration with Diego Blas and Christopher McCabe.

Progress Towards a Continuous Offline Source of Francium-223 Atoms for Magneto-Optical Trapping

Wesley Cassidy, University of Chicago

We are developing an experiment to measure the Nuclear Schiff Moment of ^{223}Fr to search for physics beyond the standard model. The nucleus of ^{223}Fr (t_1/2=22min) has a static octupole deformation [1] that makes it highly sensitive to CP-violating physics. By binding ^{223}Fr to Ag (silver) using standard bialkali molecule assembly techniques, we will assemble strongly ionic FrAg molecules [2] that offer unprecedented sensitivity to hadronic CP violation [3]. To produce sufficient flux of ^{223}Fr, we are developing a continuous offline source of ^{223}Fr, fed from the radioactive decay of long-lived ^{227}Ac ($t_{1/2}$=22yr). We will use a 700C oven to milk Fr atoms out of Ac, ionize ^{223}Fr and no other decay daughters of ^{227}Ac, transport the beam of Fr+ ions to a trapping region, then neutralize the Fr+ and create a vapor cell MOT of Fr atoms. Our protocol combines features from several established techniques [4]. We present progress towards tests of the system using Rb, and plans for the remainder of the offline francium source.

[1] Spevak, Auerbach & Flambaum (1997). Enhanced T-odd, P-odd electromagnetic moments in reflection asymmetric nuclei. PRC, 56, 1357.
[2] Fleig & DeMille (2021). Theoretical aspects of radium-containing molecules amenable to assembly from laser-cooled atoms for new physics searches. NJP, 23(11), 113039.
[3] Marc, Hubert & Fleig (2023). Candidate molecules for next-generation searches of hadronic charge-parity violation. PRA, 180, 062815.
[4] Gwinner & Orozco (2022). Studies of the weak interaction in atomic systems: towards measurements of atomic parity non-conservation in francium. Quantum Sci. Technol. 7(2), 024001.

Investigation on Critical Exponents of Quantum Phase Transition in Optical Lattice with Kibble Zurek Mechanism

Xuzong Chen, Peking University

We reported that our investigation on the quantum phase transition from superfluid to Mott insulators in optical lattice, we measured critical exponents of quantum phase transitions with Kibble-Zurek mechanism. We also use improved band-mapping method to measure critical exponents of quantum phase transitions from 3D to 2D crossover in optical lattice with Kibble-Zurek mechanism. Beside the measurement of critical exponents of quantum phase transitions, we demonstrate the critical dynamics under dimensional crossover involving many-body phase transitions by continuously suppressing correlations and tunnelings along one direction of bulk materials. This provides a smooth connection from higher dimensions to lower dimensions based on intrinsic correlations instead of geometry tailoring. By measuring the non-adiabatic excitations, both critical scaling laws in 3D and 2D are observed and consistent with predictions. Besides, we find new scaling behaviors for intermediate regimes with non-integer dimensions. This provides new insights to extend critical exponents descriptions into more general or complex scenarios.

[1] Qinpei Zheng , Yuqing Wang , Libo Liang, Qi Huang, Shuai Wang , Wei Xiong, Xiaoji Zhou, Wenlan Chen , Xuzong Chen, and Jiazhong Hu，Dimensional crossover of quantum critical dynamics in many-body phase transitions， Phys. Rev. Res.5, 013136 (2023).
[2] Qi Huang, Ruixiao Yao, Libo Liang, Shuai Wang, Qinpei Zheng, Dingping Li, Wei Xiong, Xiaoji Zhou, Wenlan Chen, Xuzong Chen, and Jiazhong Hu， Observation of many-body quantum phase transitions beyond the Kibble-Zurek Mechanism， Phys. Rev. Lett. 127, 200601 (2021).

Spin- and Momentum-Correlated Atom Pairs Mediated by Photon Exchange and Seeded by Vacuum Fluctuations

Panagiotis Christodoulou, ETH Zurich

Engineering pairs of massive particles that are simultaneously correlated in their external and internal degrees of freedom is a major challenge, yet essential for advancing fundamental tests of physics and quantum technologies. We experimentally demonstrate a mechanism for generating pairs of atoms in well-defined spin and momentum modes. This mechanism couples atoms from a degenerate Bose gas via a superradiant photon-exchange process in an optical cavity, producing pairs via a single channel or two discernible channels. The scheme is independent of collisional interactions, fast and tunable. We characterize the emergent pair statistics and find that the observed dynamics is consistent with being primarily seeded by vacuum fluctuations in the corresponding atomic modes. Together with our observations of coherent many-body oscillations involving well-defined momentum modes, our results offer promising prospects for quantum-enhanced interferometry and quantum simulation experiments using entangled matter waves.

Electromagnetic sensing with hot Rydberg atoms

Maxime Debiossac, DLR, Institute of Quantum Technologies

Rydberg atom-based quantum sensors are gaining increasing attention due to their unique sensing capabilities and advantages over conventional techniques. They are absolute, drift-free and are not prone to aging effect and therefore do not require calibration. Rydberg-based quantum sensors operate at room temperature, without the need for cryogenic cooling nor active pumping mechanism. For that reason, they are perfectly suited for miniaturization in the future. Using the experimental platform of thermal vapors in glass cells, I will show how Rydberg atoms can be exploited for electromagnetic field sensing with promising applications in radar and communications, battery diagnostic and space weather monitoring.

Towards large momentum atom interferometry in strontium for fundamental physics

Soumyodeep Dey, University of Birmingham

As a part of the Atom Interferometer Observatory and Network (AION) project, the team at the University of Birmingham is working on the enhancement of large momentum transfer in atom interferometry for strontium, to support the future science goals of AION. The goal includes building of a km-scale base line atom interferometer for the detection of gravitational wave and search for ultra-light dark matter. This large-scale sensor will work with other similar sensors around the world building an observatory network.

The relative phase difference between the two arms of an atom interferometer is proportional to the effective momentum transfer between them. To contribute to search for mid-band gravitational

waves and ultra-light dark matter it will be necessary to increase large momentum transfer by large momentum transfer (LMT) beyond the current state of the art of 400 $\hbar$k, with an ultimate aim of exceeding 10000 $\hbar$k. We aim to increase the momentum separation over 1000 $\hbar$k in our laboratory system, through application of tailored atom-optical pulse schemes, wave front control and hybrid atom interferometry schemes. The findings from our laboratory will be implement in future to AION-km project.

Shell-shaped BEC: many- and few-body physics

Maxim Efremov, German Aerospace Center (DLR), Institute of Quantum Technologies

Ultracold quantum gases confined in three-dimensional bubble traps are promising tools for exploring many-body effects on curved manifolds. As an alternative to the conventional technique of radio-frequency (rf) dressing [1], we propose to create such shell-shaped Bose-Einstein condensates (BECs) in microgravity based on dual-species atomic mixtures [2], and we analyze their properties as well as the feasibility of realizing [3] symmetrically filled shells. Beyond similarities with the rf dressing method, as in the collective excitation spectrum, our approach has several natural advantages like the robustness of the created quantum bubbles and the possibility of magnifying shell effects through an interaction-driven expansion.

Moreover, to significantly extend the observation time of the condensate shell during its free expansion and enables the study of novel quantum many-body effects on curved geometries, we have proposed a straightforward implementation of matter-wave lensing techniques for shell-shaped BECs. We have obtained optimal parameters for realistic lensing schemes to conserve the shell shape of the condensate for times up to hundreds of milliseconds [4].

In addition, we have found Confinement induced resonances (CIRs) in a system of two bosonic particles, which are confined in a spherically symmetric shell-shaped trap and interact with each other via a three-dimensional zero-range potential [5]. These CIRs are shown to occur at certain values of the shell radius and originate entirely from the strong coupling of the relative and center-of-mass motions of the two particles. This offers a new way to control the atom-atom interaction in the atomic gas by tuning only the geometrical parameters of the shell.

[1] R.A. Carollo, et al., Observation of ultracold atomic bubbles in orbital microgravity. Nature 606, 281–286 (2022)
[2] A. Wolf, P. Boegel, M. Meister, A. Balaž, N. Gaaloul, and M.A. Efremov, Shell-shaped Bose-Einstein condensates realized with dual-species mixtures, Phys. Rev. A 106, 013309 (2022)
[3] F. Jia, Z. Huang, L. Qiu, R. Zhou, Y. Yan, and D. Wang, Expansion Dynamics of a Shell-Shaped Bose-Einstein Condensate, Phys. Rev. Lett. 129, 243402 (2022)
[4] P. Boegel, A. Wolf, M. Meister, M.A. Efremov, Controlled expansion of shell-shaped Bose–Einstein condensates, Quantum Science and Technology 8, 034001 (2023)
[5] C.M. Carmesin and M.A. Efremov, Confinement Induced Resonances in Spherical Shell Traps, arXiv:2401.14946 (2024)

Matter-wave interferometry for probing the physics of many-body quantum systems

Christopher Foot, University of Oxford

We form a precisely controllable double-well potential for quasi-2D Bose gases by dressing atoms with multiple RFs, in a magnetic quadrupole trap. After a time-of-flight expansion the two clouds overlap to produce interference fringes, from which we determine both the local relative phase of the initial wave functions and the vortex density. Using this approach, we have probed the universal dynamics triggered by a quench from the superfluid to normal phase across the Berezinskii-Kosterlitz-Thouless critical point in a 2D Bose gas of rubidium atoms. Splitting a 2D gas in two, separated by a few microns, suddenly halves the density to quench the system across the critical point. Probing the subsequent relaxation dynamics with matter-wave interferometry, we found that the time evolution of both the phase-correlation function and vortex density obeys universal scaling laws. This conclusion is interpreted by real-time renormalization group theory [1].

[1] S. Sunami et al., Universal scaling of the dynamic BKT transition in quenched 2D Bose gases. Science, 382, 443 (2023).

Spin squeezed states under the influence of holes

Tanausú Hernández Yanes, Institute of Physics PAS

Spin-squeezing in systems with single-particle control is a well-established resource of modern quantum technology. Applied in an optical lattice clock it can reduce the statistical uncertainty of spectroscopic measurements. In these works, we consider the influence of holes in the dynamic generation of spin-squeezing with ultra-cold bosonic atoms with two internal states loaded into an optical lattice in the strongly interacting regime.

We show that anisotropic interactions and inhomogeneous magnetic fields generate scalable spin-squeezing if their magnitudes are sufficiently small, but not negligible.

We describe the analytical limiting cases of zero and infinite effective tunnelling to approximately bound the dynamics of the corresponding t-J models. We also analyse the usefulness of such states under the influence of holes for entanglement certification.

Fermionic gates for analog-digital hybrid quantum simulation simulations

Timon Hilker, University of Strathclyde

Neutral atoms in optical lattices simulate the Hubbard model with great accuracy but many problems of strongly correlated fermions are governed by more complex Hamiltonians. With digital gates based on the controlled motion of fermionic particles in superlattices, an analogue quantum simulator can be upgraded to a hybrid platform capable of running also discretized quantum algorithms. This promises to unlock a powerful approach to state preparation, detection in rotated bases, and simulations of long-range interactions and lattice gauge models. In comparison to spin-based quantum computers, the fermionic hardware automatically implements the exchange statistics and preserves quantum numbers like particle number and total spin leading ultimately to a Fermionic quantum computer.

I will present our progress in constructing a Lithium-6 machine with a second-scale cycle time and show the first experiments with our phase-stable optical superlattice. We implement single-particle tunnelling gates with above 99% fidelity and study correlated quantum walks and coherent pair-breaking. Furthermore, we are investigating applications ranging fromtrial wavefunctions of quasi-particles in doped Fermi Hubbard models to first quantum chemistry simulations and lattice gauge protocols.

Towards Magic-Trapped Atom Interferometry for Inertial Sensing and Gravimetry

Emmett Hough, University of Washington

Free-fall atom interferometers (AIs) are already an established platform for precision measurement and quantum sensing [1,2]. However, increasing the sensitivity of such AIs requires drop towers hundreds of meters long or operation in micro-gravity environments. Recently, a new paradigm of trapped atom interferometers has demonstrated up to 70 seconds of coherence for an AI held in an optical lattice [3]. Many challenges pertinent to the phase stability of lattice trapped atom interferometers limit the spatial separation of the two interferometer arms. Decreasing decoherence in trapped AIs may be possible by confining atoms in an excited band and operating the lattice at a “magic depth,” where the band energy is insensitive to lattice depth fluctuations. This technique has already been shown to increase the visibility of a free-space Mach-Zehnder interferometer [4].

In recent work [5] we have investigated phases for many BOs for both the ground and first excited bands. Here we report on work towards ultracold Yb atom trapping in the excited bands of a vertically-oriented optical lattice, operated at a magic depth. We plan to use this to develop trapped AIs at magic depths. Such AIs can be used for precision gravimetry including measurement of g, gravity gradiometry, and equivalence principle tests (using two different Yb isotopes), as well as accelerometry and inertial sensing.

[1] Morel et al., 2020. Nature 588, 61-65.
[2] Asenbaum et al., 2020. Phys. Rev. Lett. 125, 191101.
[3] Panda et al., 2022. arXiv:2210.07289.
[4] McAlpine et al., 2020. Phys. Rev. A. 101, 023614.
[5] Rahman et al, 2024, Phys. Rev. Research 6, L022012.

Rotating atom interferometer for onboard quantum inertial sensing

Vincent Jarlaud, Exail

The exquisite precision of atom interferometers has sparked the interest of a large community for use cases ranging from fundamental physics to geodesy and inertial navigation. However, their practical use for onboard applications is still limited, not least because rotation and acceleration are intertwined in a single phase shift in free-fall atom interferometers, which makes the extraction of a useful signal more challenging. Moreover, the spatial separation of the wave packets due to rotations leads to a loss of signal.

Here we present an atom interferometer operating over a large range of random angles, rotation rates and accelerations. An accurate model of the expected phase shift allows us to untangle the rotation and acceleration signals. We also implement a real-time compensation system using two fibre-optic gyroscopes and a tip-tilt platform to rotate the reference mirror and maintain the full contrast of the atom interferometer.

Using these theoretical and practical tools, we reconstruct the fringes and demonstrate a single-shot sensitivity to acceleration of 24 µg, for a total interrogation time of 2T = 20 ms, for angles and rotation rates reaching 30° and 14°/s respectively. Our hybrid rotating atom interferometer unlocks the full potential of quantum inertial sensors for onboard applications, such as autonomous navigation or gravity mapping.

Angular Bloch Oscillations and their applications

Bernd Konrad, German Aerospace Center (DLR), Institute of Quantum Technologies

To advance precise inertial navigation, we present a compact quantum sensor which is based on novel quantum phenomenon of the angular Bloch oscillations [B. Konrad and M. Efremov, Angular Bloch Oscillations and their applications, arXiv:2402.12826 (2024)] and measures solely the angular acceleration of slow external rotation. We investigate the dynamics of ultra-cold atoms confined in a toroidal trap with a ring-lattice along the azimuth angle, realized with the superposition of two copropagating Laguerre-Gaussian beams. In the presence of external rotation of small angular acceleration, or prescribed linear chirp between the two beams, the measured angular momentum of trapped atoms displays a specific periodic behaviour in time, which we name as the angular Bloch oscillations. This discovered quantum phenomenon is shown to be a key element of fruitful applications for (i) an efficient transfer of quantized angular momentum from light field to atoms, and (ii) realization of compact quantum sensor to measure exclusively the angular acceleration of external rotation.

Parity violation in laser-coolable chiral molecules

Adam Koza, University of Warsaw

Laser cooling is an excellent method to control molecules for precision measurement, quantum information, many-body physics, and fundamental physics applications. However, asymmetric top molecules (ATMs), due to their complex internal structure, are challenging for experimental manipulation. Although potentially difficult to produce, ultracold ATMs offer many qualitatively unique features useful for a broad range of science. Chiral molecules, from the definition, are classified as ATMs. Precise spectroscopy of such molecules can probe small shifts caused by parity violation effects (PV) in vibrational spectra of right- and left-handed enantiomers. In this study, we investigate the possibility of laser cooling of chiral systems like M-OCHDT, where M is a heavy metal atom, e.g. ytterbium (Yb). For this purpose, we calculate Frank-Condon factors using quantum chemistry methods. Next, we analyze parity violating potential along selected normal modes with Dirac-Coulomb Hamiltonian. Finally, we estimated PV shifts for selected vibrational transitions by solving the vibrational Schrodinger equation. We found out that for chiral isotopologues of symmetric top molecules, one can keep high values of FCFs and perform effective laser-cooling. In that way, the measurement of PV shifts on ultracold chiral molecules seems to be performed soon by experimentalists.

Polarizabilities as Probes for P and/or T Violation

Sebastian Lahs, Laboratoire Aimé Cotton / Université Paris-Saclay

Searches for violations of the fundamental symmetries of parity P and time reversal T in atomic and molecular systems provide a powerful tool for precise measurements of the physics of and beyond the standard model. In this work, we investigate how these symmetry violations affect the response of atoms and molecules to applied electric and magnetic fields. We recover well-known observables like the P-odd, T-odd spin-electric field coupling that is used for searches of the electron electric dipole moment (EDM) or the effect of P-odd, T-even optical rotation in atomic gases. Besides these, we obtain several other possible observables. This includes, in particular, effects that can only be seen when using oscillating or inhomogeneous fields.

Searching for chameleon fields using atom interferometry

Bryony Lanigan, Imperial College London

There are a number of models that aim to reconcile the observed accelerating expansion of the universe with our current understanding of general relativity [1]. One interesting model proposes the existence of a scalar field that is screened in regions of high matter density and can therefore go unnoticed in experiments performed on Earth – colloquially referred to as the 'chameleon field' [2-4].

In 2015 Burrage et al showed that atoms inside a vacuum chamber are too small to screen the chameleon field and could therefore be used as a probe to measure it [5]. Since then a number of experimental searches have been undertaken using cold atoms, but have so far failed to observe its existence [6-8].

Here, we describe a number of upgrades to our experiment at Imperial College that improve our precision and reduce systematic sources of errors. We are now planning a series of experiments that will probe the remaining region in parameter space where a signature of the elusive chameleon field may exist.

[1] E. J. Copeland, M. Sami, and S. Tsujikawa, Int. J. Mod. Phys. D 15, 1753 (2006).
[2] J. Khoury and A. Weltman, Phys. Rev. Lett. 93 (2004).
[3] J. Khoury and A. Weltman, Phys. Rev. D 69 (2004).
[4] P. Brax, C. van de Bruck, A.-C. Davis, J. Khoury and A. Weltman, Phys. Rev. D 70 (2004).
[5] C. Burrage, E. J. Copeland, and E. A. Hinds, J. Cosmol. Astropart. Phys. 03 (2015).
[6] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Mller, J. Khoury , Science 349, 849 (2015).
[7] M. Jaffe, P. Haslinger, V. Xu, P. Hamilton, A. Upadhye, B. Elder, J. Khoury, and H. Müller, Nat. Phys. 13, 938 (2017).
[8] D. O. Sabulsky, I. Dutta, E. A. Hinds, B. Elder, C. Burrage, E. J. Copeland, Phys. Rev. Lett. 123 (2019).

Quantum Correlated Probes For Weak Field Sensing

Timothy Leese, The Open University

Cold atoms offer a promising platform for quantum computing, employing optical tweezers to hold atoms while lasers control the qubit states for quantum logic gates. One suitable protocol for cold atoms is deterministic quantum computation with one clean qubit (DQC1). This method can be adapted into a phase estimation scheme [1] for quantum sensing, improving on a standard atom interferometer by using entanglement to surpass the shot noise limit.

This poster presents our progress toward implementing DQC1. We have made improvements in our experiment based around a mesoscopic dipole trap with a waist of ≈ 2 μm holding ≈ 50 atoms at a temperature ~ 120 μK. For coherent control of qubits, we are developing a noise-tolerant laser system that drives Raman transitions between two hyperfine ground states via an excited state in a λ-configuration. Two lasers excite a narrow ~ 700 kHz FWHM spectral feature from electromagnetically induced transparency (EIT). By stabilising one laser to a saturation absorption spectrum and the other to the EIT signal, we minimise relative frequency noise. In addition, we present modelling of λ-enhanced grey molasses which other work has shown cooling to ~ 4 μK in 87Rb. We will implement grey molasses by adapting our laser system. This temperature reduction is necessary to minimise atomic thermal motion, which we expect will decrease decoherence in quantum gates and enhance our ability to initialise and readout quantum states.

[1] Calum MacCormick et al. Phys. Rev. A 93, 023805 (2016).

Expanding Earth Science with Atom Interferometry

Jeremiah Mitchell, University of Cambridge

Atom interferometry is a quantum sensor technology that uses ultra-cold atoms placed in entangled quantum states to detect minute changes in local fields arising from gravitational waves and ultra-light dark matter. Their extreme sensitivity to accelerations has been demonstrated for measurements of Newton's gravitation constant, tests of the Equivalence Principle, and measurement of local gravity gradients [1-3]. In understanding the fundamental systematics and backgrounds of these detectors, we have discovered that atmospheric and seismic effects, even though physically decoupled from the atoms which are in vacuum and free-fall, are still detectable by the quantum phase of the atoms [4-6]. From a different perspective these "noise" sources are also interesting signals that we may be able to understand better with these sensor platforms leading to cross-disciplinary studies in Earth sciences.

I will present the potential pathways to enabling atom interferometers for the Earth sciences with a presentation of current simulation and modeling efforts and a discussion of the future outlook.

[1] Bongs, K. et al., Nat Rev Phys 1, 731–739 (2019).
[2] Overstreet, C. et al., Phys. Rev. Lett. 120, 183604 (2018).
[3] Asenbaum, P. et al., Phys. Rev. Lett. 118, 183602 (2017).
[4] Mitchell, J., Kovachy, T., Hahn, S., Adamson, P. & Chattopadhyay, S., J. Inst. 17, P02001 (2022).
[5] Badurina, L. et al., Phys. Rev. D 107, 055002 (2023).
[6] Harms, J., Living Rev Relativ 22, 6 (2019).

Trapping SrOH for Measurements of Fundamental Physics

Abdullah Nasir, Harvard University

Laser-coolable polyatomic molecules containing heavy nuclei have great potential as tools for probing fundamental physics, such as being used to search for the electron electric dipole moment (eEDM). These benefits are largely due to the many degrees of freedom that a complex molecule possesses; however, this structure also makes cooling and trapping the molecules difficult. To date, only one other polyatomic molecule, CaOH, has been laser-cooled and trapped in a magneto-optical trap (MOT). SrOH, which has many of the same characteristics that made it possible to laser-cool CaOH [1, 2] also has sensitivity to Beyond the Standard Model physics. To that end, we here report a MOT of SrOH containing 10^3 molecules. We will also discuss our next steps towards a precision measurement using SrOH, including finding further vibrational repumpers, sub-doppler cooling, and loading into an ODT.

[1] Kozyryev et al., PRL, 2017.
[2] Lasner et al., PRA, 2022.

Searches for Variation of Fundamental Constants With Cold Molecules and Interferometers

Lukas F. Pasteka, Comenius University / University of Groningen

We propose two specific avenues towards the experimental searches for the variation of fundamental constants (namely, the fine structure constant α and the proton-to-electron mass ratio μ) based on computational modeling. The first is based on the enhanced sensitivity in molecular spectroscopy and the near-cancellation between the spin-orbit (fine-structure) and vibrational levels, exemplified by the case of the $X^2\Pi$ dihalogen and halogen-hydride cations. The second explored route is based on the increased instrumental precision of laser interferometry and the dependence of bulk crystal structure on the fundamental constants. Both options offer several orders of magnitude of improvement over the usual atomic clock searches.

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

Guanchen Peng, Imperial College London

The Standard Model of particle physics cannot explain the observed antimatter-matter imbalance. This imbalance requires additional CP violation, one signature of which is the electron's electric dipole moment (eEDM) [1]. The eEDM is predicted to be approximately 10^{-35} e·cm in the Standard Model (SM), but larger than 10^{-31} e·cm in most theories Beyond the Standard Model (BSM). Therefore, eEDM measurements can decisively distinguish between SM and BSM physics.

We present our plan to measure the eEDM with YbF molecules trapped in an optical lattice and our progress towards this goal. We use a two-stage cryogenic buffer gas source [2] to produce a molecular beam whose velocity distribution peaks at 49 m/s [3]. We use radiation pressure slowing to decelerate this beam so that it can be captured in a magneto-optical trap, which we have built. We measure a leak out of the cooling cycle at a few parts in 104, which we attribute to decay to low-lying states arising from inner-shell excitation [4]. We will summarise our spectroscopic studies of these "4f hole" states [5].

[1] M. Pospelov and A. Ritz. Phys. Rev. D, 89:056006 (2014).
[2] H.I.Lu et al. Phys. Chem. Chem. Phys., 13, 18986-18990 (2011).
[3] A. D. White et al. In preparation.
[4] C. Zhang et al. J. Mol. Specrosc. 386, 111625 (2022).
[5] S. Popa et al. PRX 14, 021035 (2024).

Elastic electron scattering from alkali earth metals- analysis using MCDF approach

Aiswarya Rajendran, Indian Institute of Technology Patna

Modelling the interaction potential for projectile-target interactions has always been a difficulty for theorists. This is because of the complex interactions that exist between them. For majority of atomic and molecular systems, a number of model potentials have been proposed, with which very excellent agreement with experimental results has been established. The present study considers electron elastic scattering from alkaline earth metals. A multi-configurational treatment is used to include the initial state correlation of the scatterer. Similarly, the final state correlation effects are also included by writing the outgoing electron as a linear combination of different states arising from different initial states. The electron density of the targets is modelled using Multi-configuration Dirac Fock (MCDF) approach, and the scattered states are analysed using Dirac partial wave analysis. A comparative assessment of available experimental and theoretical results will be given.

Quantum Logic Spectroscopy of the Hydrogen Molecular Ion

Fabian Schmid, ETH Zurich

I will present our latest results, implementing pure quantum state preparation, coherent manipulation, and non-destructive state readout of the hydrogen molecular ion H2+. The hydrogen molecular ion H2+ is the simplest stable molecule, and its structure can be calculated ab-initio with high precision. By comparing the calculations with experimental data, fundamental constants can be determined, and the validity of the theory itself can be tested. However, challenging properties such as high reactivity, low mass, and the absence of rovibrational dipole transitions have thus far strongly limited spectroscopic studies of H2+. We trap a single H2+ molecule together with a single beryllium ion using a cryogenic Paul trap apparatus, achieving trapping lifetimes of 11 h and ground-state cooling of the shared axial motion [1]. With this platform we have recently implemented quantum logic spectroscopy of H2+. We utilize helium buffer gas cooling to prepare the lowest rovibrational state of ortho-H2+ (rotation $L = 1$, vibration $\nu = 0$). We combine this with quantum logic operations between the molecule and the beryllium ion for the preparation of single hyperfine states and non-destructive state readout and demonstrate Rabi flopping on several hyperfine transitions. Our results pave the way for high precision spectroscopy of H2+ which will enable tests of theory, measurements of fundamental constants, and an optical molecular clock.

[1] N. Schwegler, D. Holzapfel, M. Stadler, A. Mitjans, I. Sergachev, J. P. Home, and D. Kienzler, Phys. Rev. Lett. 131, 133003 (2023).

On the properties of charged Bose polarons

Laurent Simons, University of Antwerp

The system of a charged impurity in an interacting Bose gas has gained significant attention due to the long-range ion-atom interactions and the possibility of probing the ion using an electric field. In our work, the polaronic ground-state energy is evaluated within the Bogoliubov approximation excluding and including beyond-Frohlich interactions, which describe the absorption and/or emission of two Bogoliubov phonons by the ion. A divergence in the polaronic energy is found indicating a transition between the repulsive and attractive polaron regime. The validity of the Bogoliubov approximation used is also investigated. The optical absorption in the case of an applied AC electric field has been evaluated for weak ion-atom and atom-atom interactions, and the effect of finite temperature has been studied. The absorption can be detected experimentally as heating of the condensate. For typical experimental parameters, a heating rate of 1-10 nK/s has been found. Experimenters can tune this heating rate to bring it in their desired regime for detection.

Optically trapping small, chemically stable molecules for future tests of fundamental physics

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Cold molecules have already proven to be a useful platform for tests of fundamental physics. The ability to trap a wider class of cold molecules is expected to improve the precision of these tests by increasing sample densities and interrogation times. To this end, we describe a novel platform for trapping a wide class of small, chemically stable (SCS) molecules: a buffer-gas-loaded optical dipole trap [1]. The trap is formed at the focus of a 1064-nm buildup cavity with continuous-wave intensities of hundreds of GW/cm^2. For typical SCS molecules, the trap depth is ~10 K, so molecules can be directly buffer-gas loaded into the trap without the need for laser cooling. The trap is run very far from any molecular resonances, so the loading and trapping mechanisms are species-agnostic, and several different species can be trapped in the same trap, even at the same time. Here, we discuss the impact of this trap on fundamental physics, outlining its potential in searches for the electron's electric dipole moment and precision molecular spectroscopy. We also discuss the impact of the high-intensity light on these measurements. Furthermore, we outline the experimental progress made towards realizing the trap, including development of robust high-intensity optical cavities and a novel buffer-gas cell design optimized for loading the trap.

[1]: Ashwin Singh, Lothar Maisenbacher, Ziguang Lin, Jeremy J. Axelrod, Cristian D. Panda, and Holger Müller. Dynamics of a buffer-gas-loaded, deep optical trap for molecules. Phys. Rev. Research 5, 033008 – Published 5 July 2023

Dark Matter Reconstruction in LBAI Experiments with Imperfect Data

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Long-baseline atom interferometer (LBAI) experiments offer unprecedented sensitivity to ultralight scalar dark matter (DM) [1], however reconstruction of a putative DM signal with traditional frequency-domain analysis requires ``perfect" data (i.e., regularly-sampled with no missing samples). In a real LBAI experiment, there will undoubtedly be imperfections in the data leading to downtime. This downtime can arise from operational considerations (e.g., maintenance), the operational environment (motion of people and animals [2] or elevators), and robustness of the experimental apparatus (e.g., bad atom launches). In this work, we investigate the impact of various downtime models on the overall DM sensitivity of such an experiment. We compare the sensitivity for each downtime model as determined by a ``compound" FFT analysis to a baseline no-downtime case. We also show how much sensitivity can be regained by moving to a Lomb-Scargle frequency analysis, as in [2]. Furthermore, we demonstrate reconstruction of the DM wave's phase as well as its frequency.

[1] D. Antypas, et al, ``New Horizons: Scalar and Vector Ultralight Dark Matter" (2022). arXiv:2203.14915
[2] J. Carlton and C. McCabe, ``From RATs to riches: mitigating anthropogenic and synanthropic noise in atom interferometer searches for ultra-light dark matter" (2023). arXiv:2308.101731

Magneto-optical Trapping of Silver Atoms

Mohit Verma, University of Chicago

Alkali-silver molecules have exceptionally large electric dipole moments, making them attractive for precision measurements and quantum simulation [1,2]. Silver also has an alkali-like atomic structure, making it amenable to standard laser-cooling and trapping techniques as well as to methods routinely applied to assemble ground-state bialkali molecules. In our lab, we are particularly interested in binding silver with francium to form FrAg molecules, which can be used to search for physics beyond the Standard Model. FrAg molecules have unprecedented sensitivity to hadronic CP-violation due to both the strong ionic Fr-Ag bond [3] and the presence of static octupole deformation in the ^{223}Fr (t1/2 = 22 min) nucleus [4]. Prior to our work, silver had only been laser-cooled once [5] due to the need for high-power UV light. We present results on magneto-optical trapping of Ag atoms, as well as progress towards determining its s-wave scattering lengths.

[1] Kłos, J., Li, H., Tiesinga, E., & Kotochigova, S. (2022). Prospects for assembling ultracold radioactive molecules from laser-cooled atoms. NJP, 24(2), 025005.
[2] Śmiałkowski, M., & Tomza, M. (2021). Highly polar molecules consisting of a copper or silver atom interacting with an alkali-metal or alkaline-earth-metal atom. PRA, 103(2), 022802.
[3] Fleig, T., & DeMille, D. (2021). Theoretical aspects of radium-containing molecules amenable to assembly from laser-cooled atoms for new physics searches. NJP, 23(11), 113039.
[4] Spevak, V., Auerbach, N., & Flambaum, V. V. (1997). Enhanced T-odd, P-odd electromagnetic moments in reflection asymmetric nuclei. PRC, 56(3), 1357.

[5] Uhlenberg, G., Dirscherl, J., & Walther, H. (2000). Magneto-optical trapping of silver atoms. PRA, 62(6), 063404.

Optical Clock Interferometry with 87Sr for the AION Project

Thomas Walker, Imperial College London

Atom interferometers (AIs) can be used to detect mid-frequency gravitational waves, and ultra-light dark matter candidates. In analogy to light-based interferometers, optical pulses are used to split and recombine atomic wave packets, and differential effects long the two paths can be observed in the final excitation fraction of the atoms. By manipulating the atoms using ultra-narrow single-photon transitions, the unparalleled accuracy of optical atomic clocks can be utilised in AIs.

In this poster, we present the experimental design for, and progress towards, clock interferometry on the 698 nm $^1S_0$-$^3P_0$ clock transition in ^{87}Sr. Atoms are cooled and state prepared in a dipole trap, where they are released into freefall and addressed by the clock laser. A series of pulses from the clock laser forms a Mach-Zehnder-type atom interferometer: first the momentum transfer from a $\pi/2$ pulse splits the atomic wave packet in space, then a π pulse acts as a mirror to bring the two paths back together, and finally a second $\pi/2$ pulse erases the which-way information and allows the paths to interfere. The implementation of the process can be verified by measuring the final atom state populations as a function of relative phase between the pulses.

This experiment is part of the development of the Atom Interferometer Observatory Network (AION), which will use differential phase measurements between multiple AIs interacting with a single clock laser. This eventually kilometre-scale experiment will use atom sources and clock interferometry techniques like the ones presented here.

Probing quantum dynamics with strongly driven ultracold atoms

David Weld, UC Santa Barbara

Degenerate gases in modulated optical potentials are a flexible testbed for the experimental study of quantum matter driven far from equilibrium. This poster presents results from a sequence of recent experiments in this area, on topics ranging from interacting quantum kicked rotors to multifractal wavefunctions and localization in driven quasicrystals. Separately, it will also discuss a new tweezer-based degenerate gas platform which aims at the study of quantum interactive dynamics.

Homogeneous fermionic Hubbard gases in flat-top optical lattices

Xing-Can Yao, University of Science and Technology of China
No abstract.