Quest of New Physics at the Precision Frontier

868. WE-Heraeus-Seminar

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Book of Abstracts

WILHELM UND ELSE HERAEUS-STIFTUNG

Abstracts of Invited Lectures

in chronological order

Nuclear magnetic structure and why it matters in new physics searches

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In precision searches for new physics in atoms and molecules, electronic theory plays a critical role in the interpretation of measurements. This interpretation relies on an understanding of nuclear properties and how these affect electronic structure. In this talk, I will explain why a better understanding of the radial distribution of the nuclear magnetic moment across the nucleus is needed to increase the new physics discovery potential in studies of fundamental symmetries violations [1,2,3], and I will give an update on the recent research developments on this topic in our group.

References

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Estimating the New Physics Sensitivity of the Th-229 Nuclear Clock

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The exceptionally low-lying isomer in Th-229 enables the realisation of a nuclear clock, with the prospect of unprecedented clock stability and ultrahigh sensitivity to new physics. The recent first laser excitation of this transition has transformed these prospects into an experimental reality. However, realising the full potential of the nuclear clock for new-physics searches requires a quantitative understanding of how the clock transition depends on nuclear structure. In this talk, I show how precision spectroscopy can be used to constrain the nuclear multipole structure of Th-229, enabling a phenomenological assessment of the sensitivity of nuclear clocks to new physics. I further demonstrate how different crystal environments surrounding the Th-229 nucleus selectively probe distinct hyperfine interactions, providing complementary information on the underlying nuclear structure and opening new opportunities for precision studies of both the nucleus and its solid-state environment.

From nuclear laser spectroscopy to the nuclear clock with Th-229

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The thorium-229 nucleus with its 8.4 eV isomer is a unique system for studies at the interface between nuclear and atomic physics, with an excitation energy in the range of transition energies of valence electrons, and accessible for the methods of precision laser spectroscopy [1]. After the first resonant laser excitation of the nuclear transition that solved the problem of searching for the accurate transition wavelength [2], there is strongly increased activity on this topic. Among possible applications, the development of a nuclear clock seems particularly attractive. This clock would offer high accuracy, high stability, and high sensitivity in clock-based tests of fundamental principles of physics, involving the strong interaction in addition to electromagnetism. There are two approaches for realizing such a nuclear clock, using either laser Mössbauer spectroscopy of thorium-doped crystals, or laser-cooled thorium ions in radiofrequency ion traps.

Important progress has been made with narrow-linewidth laser sources for the required radiation at 148 nm. While four-wave-mixing of nanosecond pulses in xenon or high-harmonic generation of an infrared femtosecond laser have been applied in the first experiments, we have now demonstrated the first CW all-solid-state laser system at 148 nm using second harmonic generation in strontium tetraborate [3]. Using this system in cooperation with the group of Th. Schumm at TU Wien, we show that the nuclear resonance can be probed with a power of less than 1 nW and that the resonance signal can be detected in absorption rather than in fluorescence [4].

References

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The solid-state approach to the nuclear clock

T. Schumm[1], I. Morawetz[1], T. Riebner[1,2], L. Toscani De Col[1], F. Schneider[1], N. Sempelmann[1], F. Schaden[1], M. Bartokos[1], G. A. Kazakov[1], S. Lahs[1], K. Beeks[1], B. Gerstenecker[1], A. Grüneis[1], M. Pimon[1], V. Lal[3], G. Zitzer[3], V. Petrov[4], J. Tiedau[3], M. V. Okhapkin[3], E. Peik[3]

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Among the >3000 isotopes, Thorium-229 provides the lowest-energy nuclear first excited state, a so-called isomeric state. This isomer at 8.4 eV excitation energy is the only nuclear state accessible to laser manipulation and spectroscopy. It's long >10 minutes lifetimes with a connected narrow transition linewidth, combined with the intrinsic robustness of nuclear transitions, makes it an exciting candidate for a "nuclear clock". The talk will report on recent developments in this field, triggered by the first laser excitation of Thorium-229 in 2024 and the first realization of a Thorium-229 nuclear clock in 2026. It will focus on the interaction of the nuclear clock transition with the solid-state environment, accessible through laser Mössbauer spectroscopy.

Ceremonial Lecture at the Helmholtz Prize Ceremony

Tuesday, 25 August 2026, at 14:20

Precision and sensitive measurements with quantum sensors:

Probing the Standard Model and beyond

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High-sensitivity and high-precision laboratory measurements have shaped the development of physics from the birth of quantum mechanics at the beginning of the 20th century. Today, such measurements are at the forefront of the quest for physics beyond the Standard Model (and even further beyond), testing fundamental symmetries, and answering the “Big Questions”. We will discuss a few examples of such experiments and present a recent puzzle stemming from high-precision atomic spectroscopy (whether or not it is resolved by the time of the meeting).

High-precision Q-value measurements for neutrino physics

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Among the most important quantities in fundamental physics for cosmology and beyond standard model theories is the effective mass of the electron (anti-)neutrino, m_ν. To date, the most constraining, least model-dependent upper limit on m_ν is set by the KATRIN collaboration with <450 meV/c^2 [1]. In complementary experiments by the ECHo [2] and HOLMES [3] collaborations the kinematics of the electron capture decay in ^{163}Ho is investigated by means of microcalorimetry. Ultimately, these experiments anticipate sub-eV limits on m_ν, where the exclusion of possible systematic uncertainties is crucial and achieved by a comparison of the calorimetrically measured Q-value of the decay to an independently measured one on the same level of uncertainty. For ^{163}Ho an uncertainty of 0.6 eV/c^2 was achieved in a direct, ultra-precise Q-value measurement using the Penning-trap mass spectrometer PENTATRAP which is more than a factor 50 more precise than the previously best measurement [4]. This technique is based on measuring the ratio of the free-space cyclotron frequencies of highly charged ions (HCIs) of the mother and daughter nuclides, the synthetic radioisotope ^{163}Ho and stable ^{163}Dy, respectively. In this frequency measurement an unprecedented fractional uncertainty of $3 \cdot 10^{-12}$ was reached. The Q-value is finally determined from the ratio of the measured cyclotron frequencies and precise atomic physics calculations of the electronic binding energies of the missing electrons in the HCIs. The talk will focus on the measurement of the electron capture Q-value in ^{163}Ho and give an outlook on future measurements that include the nuclides ^{241}Pu and ^{7}Be whose decay spectra are investigated by the Magneto-ν [5] and BeEST [6] collaborations, respectively, with the aim of placing stringent bounds on the existence of sterile neutrinos.

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Transient Signals of New Physics with Quantum Sensors

Jason Arakawa[1], Charles Cheung[1], Joshua Eby[2], Marianna Safronova[1,3], Volodymyr Takhistov[4], and Hani Zaheer[1]

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Ultralight bosonic (ULB) fields with mass $m_\phi \ll 1$ eV often arise in theories beyond the Standard Model (SM). If such fields exist, violent astrophysical events could produce bursts of high-density relativistic ULB fields. These events may also result in emission of gravitational wave, photon, or neutrino signals. Detection of the ULB fields in terrestrial or space-based laboratories correlated with the other standard astrophysical signals opens a novel avenue for multimessenger astronomy [1]. Additionally, these astrophysical events may be directly connected to dark matter, such as boson star explosions, known as bosenovae [2,3]. I will discuss how quantum sensors are particularly well-suited to observe emitted scalar and pseudoscalar axion-like ULB fields coupled to SM.

References

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Next-to-leading effects in isotope shifts

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The isotope shifts (IS) of atomic spectra can be measured and theoretically calculated with high accuracy, and are therefore widely used for determining differences in the nuclear mean-square charge radii of isotopes. A proper understanding of next-to-leading IS effects becomes essential at the level of precision of modern radius determinations. Another pressing need for their systematic studies has recently emerged in the context of new-physics searches based on nonlinearities of King plots [1-4]. A King plot is a graphical representation of IS's for (at least) two transitions across several isotope pairs. Since it is expected to be linear to very high accuracy, it has been proposed [5] that a hypothetical new-physics boson coupling electrons and neutrons could manifest itself as a small deviation from its linearity. However, a number of "old-physics" effects also induce King-plot nonlinearities. Reliable theoretical understanding of these effects is therefore essential for interpreting observed deviations from linearity [1-4]. In my talk I discuss the theory of the next-to-leading field-shift and mass-shift effects in atomic spectra, which are required for interpretation of King-plot nonlinearities.

References

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Nuclear polarization beyond Coulomb approximation

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High-precision tests of the Standard Model in atomic systems offer a wide variety of opportunities to search for new physics. However, many such tests are becoming increasingly limited by theoretical uncertainties stemming from various nuclear-structure effects. Among those, the most uncertain and challenging contribution is the so-called nuclear-polarization correction, which accounts for the internal nuclear structure beyond the finite-nuclear-size effect. In this context, the full electromagnetic electron-nucleus interaction consists of a Coulomb part and a transverse term. The latter incorporates the effects of nuclear currents and is often neglected based on the argument that the velocities associated with nuclear dynamics are predominantly nonrelativistic. However, this approximation has been shown to be less accurate than initially assumed [1, 2], and in this talk we examine some of the counterintuitive and sizable effects arising from the transverse part of the nuclear-polarization correction.

References

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Precision Spectroscopy of Antiprotonic Systems

G. Baptista[1] for the PAX collaboration

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When it comes to testing the Standard Model (SM), an alternative method to high-energy particle collision for finding new physics is to shift to the precision regime. The goal of PAX is to test the best understood Quantum Field theory, Quantum Electrodynamics, in extreme bound systems composed of a nucleus and an orbiting antiproton [1,2]. The high mass of the antiproton (≈1836 that of the electron) allows it to populate Rydberg states in the antiprotonic atom that are 2000 times closer to the nucleus than in its electronic counterpart.

With access to new superconducting detector technologies, PAX is employing TES microcalorimeters to measure x rays emitted by these systems at a previously unreachable level of precision [3].

We present recent results for selected antiprotonic x ray transitions in Silicon and Zirconium, which already display a great accuracy improvement compared to previous measurements [4]. These new achievable levels of precision can be a key factor to setting new bounds to possible new hadronic interactions [5] and dark matter searches by cosmic antiproton flux measurements [6].

References

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Self-consistent bounds on Beyond the Standard Model bosons from spectroscopy of muonic atoms with magic nuclei

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Spectroscopy of muonic atoms is, to date, the most accurate technique to extract moments of the nuclear charge density because of a large overlap of the muonic wavefunction with the nucleus. The same reason makes them a prime system to check for Beyond the Standard Model influences. With the recent resolution of the fine-structure anomaly in muonic Zr, Sn, and Pb [1,2], three new, high-precision measurements are available to derive bounds on new particles. I will present these bounds and highlight the need for self-consistency in this context to ensure a clear separation between BSM and SM effects [3].

References

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An entanglement scheme to measure atomic parity violation at sub 0.1% precision

D. P. L. Aude Craik[1]

[1] *ETH Zurich, Zurich, Switzerland*

In this talk, I will discuss our project to measure atomic parity violation at unprecedented precision in barium ions. We will achieve this using our proposed entanglement scheme [1] and an ion trap featuring integrated photonics to produce a crossed-standing-wave light field. The two-ion version of the measurement will be sensitive to new physics at mass scales up to 60TeV. With the use of integrated photonic waveguides, our protocol can be implemented in an architecture that is scalable to larger ion numbers, with a proportional increase in measurement precision.

References

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Quantum Logic Control of Molecular and Transition-Metal Ions

F. Wolf[1], T. Rehmert[1,2], M.J. Zawierucha[1,2], S. Noël[1], V. N[1] and P.O. Schmidt[1,2]

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Extending quantum control to increasingly complex systems is essential for advancing quantum technologies and probing fundamental physics. Molecules, in particular, serve as highly sensitive systems for detecting symmetry violations that may reveal physics beyond the Standard Model. However, their complex level structure makes quantum-state control challenging.

Quantum logic spectroscopy offers a promising path forward for molecular ions: a well-controlled atomic ion is co-trapped with a molecular ion and enables manipulation and readout of its quantum state via shared motional modes. I will present an overview of our latest results and concepts in quantum logic control of molecular ions. As we progress toward quantum logic spectroscopy of single molecular MgH^+ ions, we are also assessing the broader applicability of these techniques to other ionic species. Recently, we demonstrated quantum logic control of a single titanium ion [1,2], showing that these methods can be extended to previously inaccessible atomic systems.

By enhancing control over new classes of ions, our work opens the door to novel applications in quantum technology and fundamental physics, making an extended range of species available for precision spectroscopy.

References

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Searching for a variation of α with highly charged ions

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Precision spectroscopy of atomic transitions is a promising tool to test our understanding of fundamental physics and search for new physics beyond the standard model. Combining the excellent precision achievable with single trapped ion clocks with the enhanced sensitivities to relativistic effects in highly charged ions (HCIs) [1,2] yields an ideal platform to search for a variation of the fine structure constant α - a possibility predicted for example by models for ultralight bosonic dark matter [3,4]. I will present the TwinTraps experiment, where we plan to perform direct simultaneous spectroscopy on two complementary highly charged ions - Cf^{15+} and Cf^{17+} - via quantum logic spectroscopy [5,6], and monitor the ratio of these two frequencies to search for a variation of α. I will present our progress on the design and construction of the experimental apparatus comprising of two identical cryogenic vacuum systems and an EBIT and ion beamline for production and delivery of the HCIs.

References

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Atom Interferometry for New Physics searches

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Atom interferometry has emerged as one of the most powerful quantum technologies for precision measurements, exploiting the wave nature of matter to probe physical phenomena with unprecedented sensitivity. By coherently manipulating atomic wave packets with laser light, atom interferometers can measure inertial forces, gravitational fields, rotations, electromagnetic interactions, and time-dependent perturbations with accuracies that often surpass those of classical sensing technologies. As advances in laser control, ultracold atom production, and large-momentum-transfer techniques continue to enhance their performance, atom interferometers are expected to play a central role in the next generation of quantum sensors.

Their scientific and technological impact extends across a broad range of applications, including high-precision navigation, geodesy and Earth observation, measurements of fundamental constants, searches for new physics beyond the Standard Model, tests of the Einstein Equivalence Principle and general relativity, as well as future gravitational-wave observatories based on matter waves. Achieving these ambitious goals requires not only increasingly sophisticated experimental platforms but also highly accurate theoretical descriptions capable of modeling quantum dynamics, laser-atom interactions, environmental perturbations, and relativistic effects.

This contribution provides an overview of the fundamental principles underlying atom interferometry and discusses modern theoretical and numerical tools developed to push the precision and accuracy of matter-wave sensors beyond the current state of the art. Particular emphasis will be placed on large-scale atom interferometers operating over long interrogation times and large baselines, where subtle systematic effects become critical. The presentation will also highlight several pioneering projects on Earth and in space, illustrating how atom interferometry is shaping the future of precision metrology, fundamental physics, and quantum sensing.

Abstracts of Selected Talks

in chronological order

Search for the variation of fundamental constants

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Several unification theories and standard model (SM) extensions predict variation of fundamental constants (VFC) in space and in time [1]. It has also been hypothesized that interaction of ordinary matter with a scalar dark matter (DM) field can produce temporal drifts or oscillations in the values of the fundamental constants [2], while topological defects in the DM field can produce transient VFC [3]. In this talk, we present two pathways towards possible detection of VFC.

A more typical spectroscopic route to observe such effects is through systematic measurements of transitions in atomic/molecular spectra sensitive to the variation of dimensionless fundamental quantities such as the fine structure constant $\alpha = e^2/\hbar c$ or the proton-to-electron mass ratio $\mu = m_p/m_e$. Enhancements due to molecular electronic structure can lead to increased detection limits [4].

Laser interferometers now reach precision far exceeding that of any spectroscopic apparatus and thus offer an alternative promising direction in the search for VFC [5]. Laser interferometers, optical cavities and resonant-mass detectors, are directly linked to measuring changes in material size. A systematic investigation of α- and μ-dependence of crystal lattice parameters and molecular bond lengths opens a new path to testing VFC and search for scalar low-mass dark matter beyond the most stringent limits [6].

References

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The enhancement of fundamental symmetry violations in atomic systems with deformed nuclei

J. Easton[1], S. Ray[1], J. Morrow[1], J. Ginges[1] and A. Borschevsky[2]

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Observations of fundamental symmetry violations in atoms and molecules via precision "table-top" experiments provide a unique probe of new physics beyond the Standard Model (BSM). Indeed, atomic parity (P) violation measurements in Cs provide some of the most stringent tests of electroweak theory at low energies. Furthermore, the search for permanent atomic/molecular electric dipole moments provides competitive constraints on additional sources of charge-parity (CP) violation arising in BSM theories.

Contributions to effects of this nature can arise from various new physics sources including nuclear electromagnetic moments induced by symmetry violating hadronic interactions, as well as through semi-leptonic interactions. In this work, we consider a variety of mechanisms inducing both P and CP odd effects in atoms and molecules, with a particular focus on nuclei with large deformation. Such systems have gained significant experimental interest due to predicted enhancements in symmetry violating nuclear moments including the magnetic quadrupole, Schiff and weak quadrupole moments [1,2].

In particular, we focus on additional contributions arising at higher orders in perturbation theory due to the combined action of P-CP odd effects with symmetry conserving electromagnetic Standard Model interactions. These combined higher order "background" effects can imitate symmetry violating signals of current interest, while also opening new avenues for experimental detection in certain systems [3]. The theoretical characterisation of such contributions will therefore assist in the planning and interpretation of future experiments. I will focus predominantly on the emergence of higher order parity violating signals that have not yet been accounted for in the literature and may influence future experiments probing the hadronic sector of the Standard Model.

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Testing Matter/Antimatter Symmetries using Cold Molecules and Antihydrogen

S. A. Jones[1,2]

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There is a contradiction between the Standard Model of Particle Physics and our observations of the Universe. Matter and antimatter should be perfectly symmetric under a charge, parity, and time transformation, yet there is no evidence for any significant quantity of antimatter surviving from the Big Bang. Symmetry tests are therefore a compelling direction towards furthering our understanding of physics and the origin of the Universe.

A sensitive way of testing the Standard Model and many beyond the Standard Model theories is to measure the size of the electric dipole moment (EDM) of the electron. The NL-*e*EDM collaboration investigates this through a spin precession experiment on a beam of laser cooled BaF molecules. The large internal effective electric field of the molecule greatly enhances the sensitivity over atomic *e*EDM measurements.

A more direct way of testing matter/antimatter symmetries is to compare the spectra of hydrogen and antihydrogen. Antihydrogen can be produced and trapped by the ALPHA collaboration at CERN and subjected to experimental investigation. This has also allowed the gravitational interaction between matter and antimatter to be tested: If you drop some antihydrogen, does it fall down or up?

In this talk I will present the latest results and plans of the NL-*e*EDM and ALPHA experiments, highlighting the complementarity of the experimental techniques.

Realization of a Thorium-229 Nuclear Clock based on Absorption Spectroscopy

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The isotope Thorium-229 has a low-energy nuclear transition that has been excited in thorium-doped crystals with laser light. This opens the perspective towards a highly stable and robust solid-state optical nuclear clock. The required laser radiation at 148 nm wavelength has so far been produced using pulsed laser systems where only a small fraction of the incident photons has been resonant with the narrow nuclear transition. We report progress in exciting the nucleus with a continuous-wave laser source and that the resonance signal can be detected in absorption rather than in fluorescence. This eliminates the slow nuclear fluorescence decay from the detection process and offers a considerable advantage for clock operation through fast signal acquisition [1,2].

References

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Thorium-229 Nuclear Clock for Dark Matter Searches

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Recently, there was a breakthrough in nuclear spectroscopy that allowed the realization of the first nuclear clock. In this contribution, I explain how we used its output frequency to search for signs of ultralight bosonic dark matter. I want to discuss which settings optimize a clock's sensitivity and which limitations currently exist. Further, an outlook will be given on projected sensitivities of future solid-state-based Th-229 clocks and how they compare to Th-229-ion systems.

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Existing experiments suffice to indirectly verify the quantum essence of gravity

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The gravity-mediated entanglement experiments employ concepts from quantum information to argue that if entanglement due to gravitational interaction is observed, then gravity cannot be described by a classical system. However, the proposed experiments remain beyond our current technological capability, with optimistic projections placing the experiment outside of the short-term future. Here we argue that current matter-wave interferometers are sufficient to indirectly prove that gravitational interaction creates entanglement between two systems. Specifically, we prove that if we experimentally verify the Schrödinger equation for a single delocalized system interacting gravitationally with an external mass, then, under one of two reasonable assumptions, the time evolution of two delocalized systems will lead to gravity-mediated entanglement.

Hybrid van Hove approach to classically mediated quantum entanglement and its implications for quantum tests of gravity

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It is a matter of ongoing discussion whether quantum states can become entangled while only interacting via a classical mediator. This lively debate is deeply interwoven with the question of whether entanglement studies can prove the quantum nature of gravity. However, the answer to this fundamental question depends crucially on which hybrid quantum-classical theory is used. In this contribution, we present the recently developed approach of hybrid van Hove theory [1,2] and show that entanglement by a classical mediator is possible within that framework [3]. After briefly recapitulating the key features of hybrid van Hove theory, we demonstrate this using the proof-of-principle example of two quantum spins coupled by a classical harmonic oscillator. Conclusively, this is illustrated by presenting the purity and concurrence of the spin-spin system as a decisive measure for entanglement. Our results further imply that quantum entanglement studies cannot rule out consistent quantum theories featuring classical gravity. Moreover, we discuss how hybrid van Hove theory bypasses prominent no-go theorems on that matter and sets limits to their original claim of universality.

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Optical clocks for new physics searches

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Optical atomic clocks are the most precise measurement instruments available today. We use them to realize the unit of time and develop them as future primary standards for time and frequency. Beyond these applications, clock comparisons have enabled us over the past several years to search for signatures of new physics at the precision frontier. In particular, we have placed stringent constraints on couplings between ultralight dark matter and ordinary matter and have set limits on possible long-term variations of the fundamental constants [1].

We are currently pursuing several approaches to substantially improve clock performance and thereby increase the sensitivity of searches for new physics. We have realized a multi-ion Sr^+ optical clock operating with up to ten ions simultaneously while achieving a fractional systematic uncertainty of only 5.3×10^{-19} [2]. Building on our previous work with $^{171}Yb^+$, we have investigated $^{173}Yb^+$ as an alternative clock species. This work has enabled a precise determination of the nuclear magnetic octupole moment of ^{173}Yb [3], helping to resolve tension between earlier experimental and theoretical results. Finally, we are investigating metastable excited states in Yb^+ that could serve as the upper states of alternative clock transitions.

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Quantum Sensing in Particle Physics and the TIQTOC Experiment

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Quantum sensing is a transformative technology whose impact is being felt in many areas of science. The use of quantum-based sensing allows scientists to access subtle effects that elude conventional sensing techniques and thus build detectors with unprecedented sensitivity or accuracy. Optical atomic clocks are one of the quantum technologies being developed for fundamental physics applications. In this talk we will present the progress in building the TIQTOC Experiment: "Trapped Ion Quantum Tests Of fundamental Constants", and see what it takes to turn an ultra-stable clock into an ultra-sensitive detector for the effects of ultra-light dark matter.

Testing time-dilation effect at the quantum level with trapped ions

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Einstein's theory of relativity assumes no direct time-dilation effect of electromagnetic potentials. This statement can be relaxed by theories beyond Einstein's framework, but has not been stringently tested so far, primarily due to its smallness. Here, we put forward schemes [1] to detect the possible time-dilation effect of electromagnetic potentials with currently available high-precision measurements of trapped ions [2-4]. In the case of a null result, it would serve as the most stringent and reliable test of Einstein's theory on this aspect. Otherwise, it would indicate a new physics that could modify our fundamental understanding of the dynamics of spacetime.

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A new era of fundamental physics tests with antihydrogen

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The absence of antimatter in our Universe as we observe it today strongly motivates direct matter-antimatter comparisons, where any observed difference would lead to new physics. The Antihydrogen Laser Physics Apparatus (ALPHA) collaboration at CERN produces and traps antihydrogen atoms by combining antiproton and positron plasmas. These trapped ensembles are then used for both spectroscopy [1] and gravitational studies [2]. One of the main limiting factors in the trapping rate of antihydrogen is the positron temperature. By sympathetically cooling the positrons using laser-cooled Be+ plasmas, we have recently achieved an eight-fold increase of the antihydrogen trapping rate [3]. A sample of over 15,000 antiatoms can now be produced in under seven hours, enabling high-statistics measurements.

Using Be-assisted antihydrogen production, we have measured the ground-state hyperfine splitting of antihydrogen a_1S/h=1,420,404.8±1.1(stat)±5.6(sys) kHz in a 1 T magnetic field, consistent with expectations for hydrogen [4]. This 4 parts per million measurement constitutes an improvement over the previous state-of-the-art of two orders of magnitude. At this level our measurement is sensitive to the internal structure of the antiproton, which contributes at about 40 ppm, and is approaching the limit of existing theoretical analyses.

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

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All-Order Vacuum Polarization Correction in Heavy Atomic Systems

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Precision tests of quantum electrodynamics (QED) with heavy atoms have attracted a growing interest in the last decades due to the extreme electric fields present in these systems. To utilize the full potential of the increasingly accurate modern experiments as a test of the Standard Model in the strong-field regime, it is necessary for theoretical QED predictions to match their precision. In this talk, we present improved nonperturbative QED calculations of the Lamb shift in heavy highly charged and exotic ions. A particular emphasis will be placed on the vacuum polarization correction to the atomic energy levels and to interelectronic interactions in few-electron, highly charged ions. Moreover, we will discuss the influence of the finite nuclear size on the Lamb shift and on the accuracy of theoretical QED predictions [1, 2].

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The MuEDM Experiment for the Search of the Muon Electric Dipole Moment: Status and Prospects

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A nonzero electric dipole moment (EDM) of a fundamental particle intrinsically violates parity (P) and time-reversal (T) symmetries. Through the CPT theorem, T violation also implies violation of the combined charge-conjugation and parity (CP) symmetry. We aim to measure the muon EDM using the frozen-spin technique in a compact storage ring [1]. This approach exploits the large effective electric field, ($E \sim 165$ MV/m), experienced in the muon rest frame by muons with a momentum of around (23 MeV/c) circulating in a solenoidal magnetic field of $|B| = 2.5$ T.

In this talk, we discuss the key principles underlying a muon EDM search and present the design of a demonstrator experiment proposed for the secondary muon beamlines at the Paul Scherrer Institute. During Phase I, assuming 200 days of data taking, the projected sensitivity is $\sigma(d) \leq 4\text{x}10^{-21}$ e·cm. In a second stage, Phase II, a dedicated setup on a higher-momentum beamline at (125 MeV/c) is expected to improve the sensitivity to $\sigma(d) \leq 6\text{x}10^{-23}$ e·cm. A partially instrumented version of the detector was operated during a test beam campaign in December 2025. The status of the experiment, together with preliminary detector performance results, will be presented.

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Precision quantum metrology with trapped Ba^+ ions for tests of fundamental physics

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Quantum metrology with trapped ions offers unique opportunities for precision measurements that probe physics beyond the Standard Model [1]. In this talk, I will present our efforts to develop a Ba^+-based quantum sensor that exploits the exceptionally long 80 s radiative lifetime of the $5^2D_{3/2}$ state, enabling coherence times that support sub-10 mHz frequency resolution. By combining entangled states with a decoherence-free subspace, we aim to suppress correlated noise and reduce uncontrolled systematic effects. This platform enables high-precision isotope shift measurements for searches for new bosons through King plot analyses [2], as well as atomic parity non-conservation (PNC) [3], providing a sensitive low-energy test of the electroweak interaction. Because PNC effects are intrinsically weak, achieving long coherence times and excellent control over systematics is essential. I will discuss the underlying concepts and present our recent experimental progress toward realizing this trapped-ion quantum sensor.

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Atomic parity violation in highly charged ^{40,48}Ca and ^{208}Pb ions

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We calculate parity-violation-induced E1 amplitudes for the $1s \rightarrow 2s$ and $1s^2 2s \rightarrow 1s^2 3s$ transitions in H- and Li-like ions of ^{40}Ca, ^{48}Ca, and ^{208}Pb. In our analysis, we account for neutron skin effects and nuclear uncertainties for each nucleus. We consider the spin-independent weak-interaction contribution of the Z^0 boson described by standard model, as well as the effects of a hypothetical new Z′ boson of varying mass. We conclude that the neutron-skin corrections in the ^{40,48}Ca isotope pair can mostly be neglected when considering Z′ boson effects, which is an advantage for the search for new parity-violating physics. On the other hand, both the neutron skin effect and the sensitivity to hypothetical Z′ interactions in ^{208}Pb are shown to be significant.

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Precision Searches for Spin-Dependent Exotic Interactions

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Spin-dependent exotic interactions [1] are well-motivated signatures of physics beyond the Standard Model. They may be mediated by new light bosons, including spin-0 particles (e.g., axions) and spin-1 particles (e.g., light Z' bosons). Such particles are also well-motivated candidates for dark matter or dark energy and may induce violations of fundamental symmetries. Recent precision searches using atomic [2,3,4] and molecular [5] spectroscopy, force sensors [6], comagnetometers [7], and atom interferometers [8] have placed stringent constraints on fermion–fermion exotic interactions, demonstrating the power of precision measurements to explore physics beyond the Standard Model.

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Ultra-light dark matter phenomenology with atom interferometers

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The development of long-baseline atom interferometers is an exciting prospect for all branches of science and metrology. Chief among these are their applications in astroparticle phenomenology from detection of gravitational waves to illuminating the nature of dark matter. Ultra-light dark matter candidates behave as classically oscillating fields and when coupled to Standard Model fundamental constants, modify measurements made when interrogating atoms. Delocalising atomic wave packets up to metres apart and interfering them coherently again significantly enhances sensitivity to these effects. The Very Long Baseline Atom Interferometer (VLBAI [1]) facility at Leibniz Universität Hannover is one such experiment with many others proposed and under construction as part of the Terrestrial Very Long Baseline Atom Interferometry (TVLBAI) community [2].

In this talk I will review how future atom interferometers will place leading experimental constraints in searches for dark matter and some of the challenges they face. I will also highlight recent work focusing on axion dark matter which induces a mass dependent coupling to atoms [3]. The VLBAI is planned to operate a dual species Rubidium-Ytterbium configuration sensitive to this coupling and may serve as a test bed for future 100+ m scale experiments such as AICE [4]. In this work we develop a robust framework applicable to dual-species atom interferometers and a comprehensive analysis of the dominant noise sources for the VLBAI [5].

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Ultralight dark matter: astrophysical and cosmological implications

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The nature of dark matter (DM) remains one of the mysteries of modern physics, which poses a challenge for the Standard Model. An intriguing possibility is to assume that DM consists of ultralight bosonic particles, which are often referred to as axion-like particles, and emerge in various extensions of the Standard Model. The ultralight bosons have unique quantum features on $\sim$ kpc scales, where they form solitons and, possibly, vortex structures of a Bose-Einstein condensate. The question of the viability of the ultralight DM (ULDM) on galactic scales can be addressed from cosmological and astrophysical perspectives, where the first explores the process of the formation of haloes in the Universe, while the second examines the observable implications of the formed ULDM haloes. In particular, we investigate such implications: rotation curves [1], velocity dispersion [2], dynamical friction of baryonic matter [3], the DM vorticity [4], and gravitational wave signatures in collisions of ULDM haloes [5]. While our results contribute to the ongoing effort to understand the ULDM, much remains to be done to reveal the nature of dark matter.

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Abstracts of Poster Presentations

in alphabetical order by presenting author

Entanglement-enhanced $^{40}Ca^+$ multi-ion clock

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State-of-the-art optical atomic clocks based on trapped ions require long interrogation times and larger ion numbers to achieve low statistical uncertainty, but both methods are limited by various noise sources. Therefore, a small number of entangled ions with Quantum Projection Noise (QPN) below the Standard Quantum Limit (SQL) might be beneficial. We have demonstrated entanglement gain leading to faster averaging and suppression of magnetic-field noise in $^{40}Ca+$ ions in a Decoherence Free Subspace (DFS)[1]. Entanglement also provides an improvement in the measurement uncertainty through a reduction in QPN. The DFS method demonstrated near-lifetime-limited interrogation, but any further gain is suppressed by spontaneous-emission events during the interrogation time. To address this, we propose an experimental implementation of an entanglement-assisted readout method that employs a 4-tone Mølmer-Sørensen gate based DFS to detect and veto spontaneous emission events from the clock feedback loop. This approach is designed to demonstrate an enhancement beyond the SQL and its scaling of the achievable lock performance with ion numbers [2].

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High-NA Objective for super-resolution fieldoscopy: Pushing the Limits of Near-Infrared Electric Field Imaging

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Fieldoscopy is a powerful technique for label-free sensing of light-matter interactions in the optical regime [1]. It captures the full electric field with attosecond resolution, providing both amplitude and phase information, while also enabling temporal gating of ultrafast dynamics and access to coherent spectral features. When such a setup is integrated into a microscope, fieldoscopy becomes particularly well-suited for studying biological and solid-state systems with sub diffraction limited resolution [2,3].

In this work, we present a next-generation microscope objective design that advances super-resolution fieldoscopy. The microscope objective pushes the spatial resolution through a numerical aperture of 1.53. In addition, the design has flat compressible dispersion making it compatible with broadband sub-5 fs laser pulses centered around 950 nm. Simulations of the design show a full width at half maximum of the point spread function of 310 nm and diffraction limited performance across the full bandwidth.

The novel sampling geometry featured in the design ensures only the excitation field interacts with the sample, while maintaining high transmission and minimal obscuration. Since the lower wavelength probe pulse does not interact with the sample photo-toxicity of the sample and influence on the sample dynamics is minimized, working towards true non-invasive fieldoscopy measurements [4].

The design is based on real, manufacturable optics and materials, alongside a custom broadband immersion oil. By using probe pulses with a lower center wavelength this system can be pushed to even higher resolutions, demonstrating a practical pathway towards sub-100 nm super-resolution, coherent imaging of ultrafast dynamics in complex systems.

Beyond fieldoscopy, the objective design is applicable to total internal reflection fluorescence microscopy, evanescent field sensing, immersion microscopy, sub-surface imaging and pump-probe schemes offering new opportunities in ultrafast biophotonics and nanophotonics.

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Single-shot fieldoscopy: real-time electric-field detection at near-petahertz bandwidth

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Probing ultrafast dynamics driven by classical and quantum ultrashort optical pulses requires direct access to the electric field of light at petahertz bandwidths [1]. Near-petahertz fieldoscopy has recently provided phase- and amplitude-resolved access to sub-cycle dynamics in ambient air, enabling label-free spectro-microscopy of liquids and solids with unparalleled spatiotemporal resolution, detection sensitivity, and dynamic range [2,3]. Yet fieldoscopy, like most field-resolved techniques, relies on temporal scanning and averaging over many laser pulses. Such averaging obscures non-repetitive or stochastic dynamics and limits waveform acquisition speed. Capturing individual optical waveforms at near-petahertz frequencies remains a central challenge.

We introduce single-shot fieldoscopy, which combines fieldoscopy with a parametric time lens to enable single-shot sub-femtosecond electric-field detection at near-petahertz frequencies and beyond [4]. Numerical simulations show that the time lens maps a near-petahertz ultrashort pulse onto the spectrum of a single laser pulse. We propose two single-shot balanced spectrometer concepts that, in combination with the parametric time lens, enable single-shot fieldoscopy: one based on angular dispersion mapped onto a high-speed CMOS sensor, and one based on the dispersive Fourier transform, supporting megahertz acquisition rates. We further address time-axis retrieval and relate key imaging properties such as temporal aperture and temporal resolution to experimental parameters including spectrometer resolution, time-lens aberrations induced by higher-order dispersion, and synchronization jitter.

Single-shot fieldoscopy delivers sub-cycle access to light-matter interactions without scanning or averaging, opening pathways to petahertz electronics, spectro-microscopy with reduced dwell times, and the study of dynamic, non-repetitive classical or quantum optical phenomena in ambient air.

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Generation and Transport of K-41 and Rb-87 mixtures in the Einstein-Elevator

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The successful creation of the first BEC in space (MAIUS-1) demonstrated the viability of matter-wave interferometry for precision physics [1], specifically for testing Einstein's Equivalence Principle (EEP). The successor apparatus MAIUS-B [2] targets dual-species interferometry using K-41 and Rb-87. Flown on a sounding rocket in December 2023, it is now transformed into a drop tower experiment in the Einstein-Elevator facility (Hannover) which provides 4 seconds of microgravity every 4 minutes.

In this talk, I will report on the experiments conducted in this drop tower, focusing on the optimization of sympathetic cooling sequences required to achieve dual degeneracy in this unique environment and on the observation of the symmetric ground state of quantum mixtures which is possible only in microgravity [3]. Furthermore, the results demonstrating the efficient simultaneous transport of the mixture using Shortcut To Adiabaticity (STA) protocols will also be presented, establishing the necessary prerequisites for high-precision EEP tests on atom chips in space.

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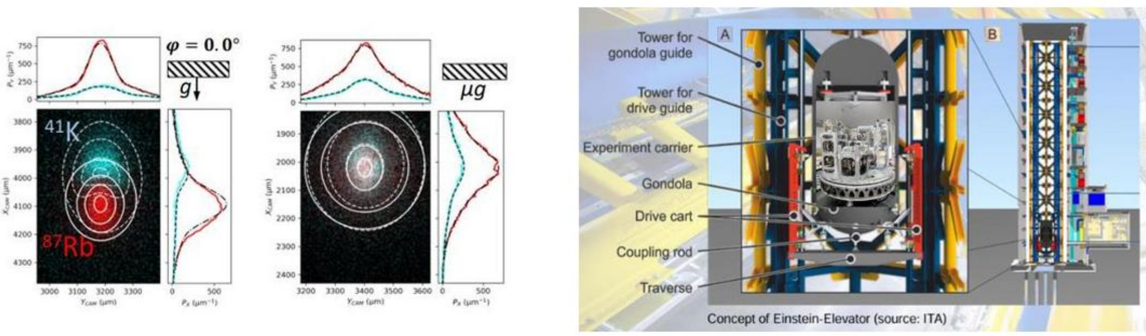

Fig 1. (left and middle) show the simulated and observed quantum mixture ensembles on ground and in microgravity [3]. (right) is the Einstein-Elevator facility with MAIUS-B inside the gondola.

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Sensitivity of Future Networks of Optical Atomic Clocks and Cavities to Scalar Ultra-Light Dark Matter

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Scalar ultra-light dark matter (ULDM) can induce oscillations of fundamental constants, making precision frequency metrology a promising probe of new physics [1]. We investigate whether spatially extended networks of optical frequency references can improve sensitivity to ULDM beyond existing laboratory constraints. We study two network-based approaches: an idealized linear network of optical cavities and searches for daily and annual sidereal modulation signatures in spatially separated atomic clocks due to the Earth's motion through the galactic dark matter halo. We find that cavity networks provide primarily statistical improvements and only modest additional benefit from spatial resolution for terrestrial baselines. For clock networks, virialized-field fluctuations strongly suppress daily signatures and significantly degrade annual-modulation sensitivity. Overall, network-based cavity and clock searches are generally not competitive with existing equivalence-principle tests [2] or projected atom-interferometric experiments [3], unless baselines of order 10^6 km or larger become available, pointing to space-based architectures as the most promising path for substantial network leverage.

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Fieldoscopy on Indium Tin Oxide Nano Crystals

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This work advances ultrafast optical spectroscopy by analysing the plasmonic resonance of a film consisting of plasmonic indium tin oxide nano crystals (ITO NC) with Fieldoscopy in the short-wave infrared (SWIR) range with attosecond precision [1]. ITO NC feature a broadband, tuneable resonant absorption band at their localised surface plasmon resonance (LSPR) frequency, which makes this material a suitable candidate for a multitude of applications, such as environmental sensing and fast optical switching [2].

For the first time, Fieldoscopy is used on ITO NC to reveal the subtle changes in the electric field oscillation of an ultrashort excitation pulse in time domain, that result from the resonant interaction of the pulse with the ITO NC. With the high sensitivity, dynamic range, and exceptional temporal resolution of Fieldoscopy [3], the ultrafast response of plasmonic ITO NC is investigated on a sub-femtosecond time scale. The material exhibits a decreased transparency in a broad spectral band around the LSPR frequency, which is measured as a change in amplitude and phase of the excitation pulse and analysed in time domain. It is further shown that this dynamic depends on the intensity of the driving field. With an increase in fluence, the optical transmission at the LSPR frequency band increases reversibly up to a fluence of 1.2mJ/cm^2, becoming irreversible for higher fluences. This way, the transmission of the material is reversibly modulated on a sub-femtosecond time scale with a modulation depth of up to 10% within the spectral band of the LSPR. This observation highlights the suitability of ITO nano crystals for the application in ultrafast optical switching on a femtosecond time scale and demonstrates the feasibility of Fieldoscopy for the investigation of plasmonic materials [1].

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Accessing higher-order radial moments of the nuclear magnetization distribution using muonic atoms together with H-like ions

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Little is known about the distribution of magnetization inside the nucleus. While nuclear charge distributions can be well understood through techniques like electron scattering, muonic atom spectroscopy, and precision measurements of atomic isotope shifts, nuclear magnetization distributions are much harder to probe. We point out and exploit a property of heavy muonic atoms that allows higher-order radial moments of the nuclear magnetization distribution to be extracted from experiment. Unlike electronic wave functions in usual atoms and ions, muonic wave functions over the nuclear extent are distinguishable for different states. We show that measurements of hyperfine constants for several different states of muonic atoms give improved access to the radial magnetization $\langle R^2 \rangle$ as well as enabling the novel extraction of $\langle R^4 \rangle$ and $\langle R^6 \rangle$. A measurement for an electronic system (H-like ion) gives additional information, though there is little if any benefit from a second electronic state. We demonstrate our approach in the nuclear single-particle model using ^{209}Bi and ^{205}Tl and show how it may be used in a model-independent way. This motivates new hyperfine measurements in muonic atoms and H-like ions and provides a unique avenue for testing nuclear structure models.

Super-resolution label-free fieldoscopy with attosecond temporal resolution

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We present a new broadband, label-free imaging approach that combines sub-diffraction spatial resolution with attosecond temporal sensitivity. Based on the principle of femtosecond fieldoscopy, the method generates 2D label-free images by exciting overtone and combination-band vibrational modes in the 1.5–2.6 μm spectral range [1]. Although a conventional optical microscope operating in this wavelength range is typically limited to resolving features of about 2 μm, fieldoscopy enables imaging beyond the diffraction limit of the excitation pulse. The transient electric field induced in the sample is captured through probe-gated nonlinear upconversion and field-resolved detection, allowing the spatial resolution to be determined by the shorter-wavelength probe focus and the nonlinear upconversion process rather than by the excitation wavelength itself. Using polystyrene beads, we measured a point spread function below 600 nm (FWHM). We further evaluated the spatial resolution with a custom polymer-based resolution target containing feature sizes from 200 nm to 2 μm, and clearly resolved structures down to 650 nm. To our knowledge, this represents the first demonstration of broadband, label-free super-resolution fieldoscopy with attosecond temporal resolution [2].

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A thorium-229 optical nuclear clock

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The laser-accessible nuclear transition in the thorium-229 isotope has been identified as a promising candidate for the realization of an optical nuclear clock [1]. Such a nuclear clock is expected to be more robust against external perturbations [2, 3] and provides enhanced sensitivity in clock-based tests of fundamental principles of physics [4, 5]. However, the required resonant laser radiation at 148 nm wavelength has so far been produced using pulsed laser systems where only a small fraction of the incident photons has been resonant with the narrow nuclear transition resulting in unwanted effects such as laser induced quenching [6] and AC stark shift. Here we present nuclear excitation with a continuous-wave narrow-bandwidth laser source and taking advantage of VUV source, we detect the excitation in absorption rather than in fluorescence. This eliminates the slow nuclear fluorescence decay from the detection process and offers a considerable advantage for clock operation through fast signal acquisition [7]. The absorption signal is then used to generate an error signal for the feedback loop to stabilize the clock laser to nuclear transition. The nuclear clock shows a simple shot-noise limited scaling of the fractional frequency instability of $3\times10^{-12}\sqrt{\tau}$ /s where τ is the averaging time, approaching 10^{-15} instabilities over 1 day of continuous operation.

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Atomic Structure of Os^{16+} and a new .yaml-based interface for the GRASP package

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The 5s–4f level crossing occurring between osmium and iridium in the Nd-like isoelectronic sequence was identified more than a decade ago as a promising feature for precision tests of fundamental physics [1]. The associated interconfiguration transitions are predicted to exhibit high sensitivity both to a possible variation of the fine-structure constant α and to violations of Einstein's equivalence principle. Nevertheless, the corresponding spectral lines have not yet been experimentally identified, despite recent efforts. Their identification is hindered in part by substantial theoretical uncertainties in the predicted transition wavelengths, lifetimes, and other radiative properties, which persist even in state-of-the-art configuration-interaction calculations [2].

In this contribution, we present *ab-initio* multiconfiguration Dirac–Fock results obtained with the GRASPG extension [3] of the GRASP package and compare them with previous theoretical predictions. In addition, we present a prototype Python package designed to simplify interaction with the command-line interfaces of the GRASP family of codes. For calculations of low to intermediate complexity, the required input can be specified in a single YAML configuration file. The package is intended to lower the barrier to entry for new users and to facilitate the automated setup of atomic-structure calculations. A live demonstration will be provided to collect community feedback and guide further development of the package.

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Relativistic Studies of Compton and Electron-Nucleus Scattering Processes

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Compton scattering, the inelastic scattering of photons by electrons, is a fundamental interaction between matter and light with applications ranging from medical radiotherapy to X-ray polarimetry. Motivated by the latter, we present theoretical investigations of Compton scattering by bound electrons, with particular emphasis on polarization effects. Our calculations are based on the relativistic S-matrix formalism and rely on a numerical solution of the radial Dirac equation for electrons in a central nuclear potential, approximated here by a Coulomb potential. This approach enables accurate calculations of the doubly differential cross section (DDCS) and the polarization properties of photons scattered by K-shell electrons over a broad energy range and for arbitrary polarization states of the incident photon beam [1].

In addition, we investigate elastic electron-nucleus scattering, an important tool for probing nuclear structure. To this end, we developed a computational framework for calculating the differential cross sections (DCS) for an electron scattered from a nucleus for electron energies up to several hundred MeV. The code connects to and extends the Compton scattering framework by allowing numerical Dirac solutions for general central potentials. In particular, the DCS for a static nuclear potential can be calculated exactly by determining the phase shifts of the continuum wave functions. Combined with a fitting procedure, it enables the extraction of nuclear charge densities and root-mean-square radii from experimental scattering data.

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New Atomic EDM Contributions Arising at Higher-Order

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Searches for atomic electric dipole moments have placed tight constraints on CP-violating BSM theories. In terms of theoretical calculations, higher-order contributions are generally assumed to be negligible. However, there exists a class of higher-order CP-violating terms that has not been systematically accounted for. These terms arise from the interplay of CP-violating operators and hyperfine electromagnetic effects, and under certain conditions, they can be comparable to terms that are included. We present a general framework for these contributions and discuss their implications for the interpretation of past experiments and the extraction of constraints on hadronic and electronic CP-violating sources.

Towards Utilizing the Very Long Baseline Atom Interferometer Facility for Precision Measurements

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Precision measurements open windows through which we can look for new physics. At the Very Long Baseline Atom Interferometer (VLBAI) facility in Hannover, we are developing an atom interferometer that aims to enhance the sensitivity scale factor $k_{\text{eff}} T^2$ by increasing the space time area enclosed by the atoms through exploiting the 10 m baseline [1], [2] , enabling free fall times up to 2 T = 2.4 s. This will allow us to take measurements of interest for different domains such as geodesy or in new physics [3] such as looking for dark matter [4] . In order to accomplish these goals, there are a series of technical demands that need to be achieved such as obtaining an ultracold sample of atoms with the number of atoms in the order of one million, with sub-nanokelvin temperatures, and manipulating their motion through efficiently launching the cold atom sample. This contribution focuses on the progress in the facility during the past year, including demonstrating atom interferometry, and the plans to achieve the full potential of the facility. These include the progress in the manipulation of rubidium atoms utilizing purely optical potentials for matter wave lensing, and control of the kinematics of the atoms for manipulation with Bragg beam splitting processes and Bloch oscillations for launching the atoms through the 10 m baseline.

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Axion Dark Matter Detection Using Atomic Clocks

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Axions are a promising dark matter candidate as well as a compelling solution to the strong charge-parity problem. Axion dark matter can be modelled as a background, classical field, whose interactions with Standard Model particles and forces give rise to observable effects. Although there are many current experiments that search for these axion-induced experimental observables, given the mystery of dark matter, it is vital to develop new experiments.

We propose a novel detection scheme using atomic clocks to detect axion dark matter. The interaction between the axion field and the electron axial-vector current can produce time-dependent mixing of opposite-parity states in atomic systems, resulting in an oscillating atomic electric dipole moment (EDM). In the presence of an external electric field, the EDM causes oscillating shifts in atomic energy levels, leading to corresponding shifts in the atomic clock frequency.

In this work, we estimate the achievable axion mass-coupling parameter space given current atomic clock performance. Preliminary order of magnitude calculations shows promising sensitivity of axion mass-coupling parameter space beyond current astrophysical and laboratory limits. We report on the optimal experimental parameters such as the clock species that maximise sensitivity while alleviating systematic error.

Successful implementation of this new detection scheme can reveal important physical axion parameters, namely axion mass and coupling parameter, as well as demonstrate a novel application of atomic clocks in the search for dark matter and atomic EDMs.

ALP Bremsstrahlung in Proton Beam Dumps & Comparisons with Constraints from Precision Experiments

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We study axion-like particle (ALP) production via proton bremsstrahlung in proton beam dumps. Using the Weizsäcker-Williams approximation and the ALPINIST framework, we compute ALP production rates and derive constraints on the product of ALP-electron and ALP-proton couplings, $g_e g_p$, via the decay channel $a \to e^+e^-$. We further assess the sensitivity of our results to the underlying QCD model by examining the dependence on light quark PQ charges. We compare our results to existing constraints from precision spectroscopy experiments, which probe the same coupling product into the MeV mass range.

Prospects for QCD axion dark matter with dual-species atom interferometers

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The development of long-baseline atom interferometers is an exciting prospect for all branches of science and metrology. Particularly for detecting ultra-light dark matter (ULDM). These candidates behave as classically oscillating fields and when coupled to Standard Model fundamental constants, modify measurements made when interrogating atoms. Delocalising atomic wave packets up to metres apart and interfering them coherently again significantly enhances sensitivity to these effects. The Very Long Baseline Atom Interferometer (VLBAI [1]) facility at Leibniz Universität Hannover is one such experiment with many others proposed and under construction as part of the Terrestrial Very Long Baseline Atom Interferometry (TVLBAI) community [2].

Axions coupled to gluons can induce oscillations in atom masses through a quadratic coupling to pions. Previous work calculated the differential phase accumulated for atom interferometers in a dual-isotope atom interferometer configuration where the difference in masses leads to a measurable signal [3]. In this work, we expand on this work to consider a true dual-species experiment planned to be conducted at the VLBAI between rubidium and ytterbium [4]. We develop a novel dual-species running configuration to enhance sensitivity while controlling systematics. In this poster, I also present our robust noise characterisation at the VLBAI, which allows us to achieve realistic projections for bounds on the QCD axion dark matter couplings in novel regions of parameter space.

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Prospects of probing atomic parity violation with vector light beams

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Atomic parity violation (APV) provides a unique low-energy probe of the electroweak sector of the Standard Model. While high-precision measurements in systems such as cesium [1] and ytterbium [2] have demonstrated the power of this approach, further progress calls for novel experimental strategies. In this contribution, we present a theoretical study of the prospects of vector light fields in APV investigations. In particular, we consider a coherent superposition of radially and azimuthally polarized beams that provides additional control of the parity violating signal. We show that such a superposition allows an enhancement of the ratio of parity-violating and parity-conserving terms by adjusting the relative strengths of the radially and azimuthally polarized beam components.

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Feasibility study of BSQED tests with antiprotonic x-ray spectroscopy with antiprotonic zirconium

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The advent of quantum sensing x-ray microcalorimeters such as Transition Edge Sensors (TESs) [1] has created exciting new opportunities to push the limits of precision physics in the hard x-ray domain. Thanks to the factor of 50 improvement in energy resolution offered by TESs over high-purity germanium [2, 3], and their high efficiency compared to crystal spectrometers [4], anti-protonic atom x-ray spectroscopy has entered a new era compared to the previous generation of experiments. The PAX project (anti-Protonic Atom X-ray spectroscopy) has employed a next-generation TES detector for spectroscopy of transitions between circular Rydberg states in antiprotonic atoms with the end goal of establishing new benchmarks for bound-state QED at field strengths well beyond the Schwinger limit with a target precision of 10^{-5} in the few hundred keV regime [5]. Details of a proof of principle study completed this year at the CERN's ELENA facility [6,7] demonstrating the feasibility of the PAX experiment will be presented along with and preliminary results and a discussion of the unique challenges for detector development related to annihilation and electromagnetic background.

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Femtosecond Stimulated Raman Fieldoscopy

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Label-free vibrational spectroscopy characterizes molecular composition by exploiting intrinsic vibrational resonances for chemical selectivity. Absorption and Raman spectroscopy probe complementary transitions, enabling multimodal sample analysis. As complex molecular systems contain various constituents at different concentrations, an ensemble of vibrational resonances must be probed simultaneously with high dynamic range. Stimulated Raman Fieldoscopy combines broadband and sensitive detection of stimulated Raman and near-infrared resonances by directly measuring the electric field of femtosecond pulses after interaction with a sample [1,2]. As chemical information is encoded in the field trailing the excitation pulse, the molecular response can be temporally separated, providing a background-free signal in amplitude and phase.

We demonstrate stimulated Raman fieldoscopy by focusing few-cycle Stokes pulses spanning 1.5–2.7 μm together with a narrowband picosecond Raman pump at 1375 nm into liquid samples. The transmitted Stokes waveform is sampled in time domain by electro-optic detection with near-single-cycle probe pulses. Pump modulation and lock-in detection isolate the pump-induced electric-field contribution from the nonlinear light–matter interaction. In addition to the stimulated Raman response, broadband Kerr modulation imprints the transmitted Stokes field onto the detected waveform, preserving access to near-infrared absorption features.

We demonstrate the technique in liquid acetonitrile, resolving Raman-active modes together with SWIR absorption features. We further apply it to acetonitrile–isopropanol mixtures over a broad concentration range, observing concentration-dependent changes in field amplitude, spectral shape, and resonance position. By measuring the electric field, stimulated Raman Fieldoscopy provides a broadband, phase-sensitive route to label-free vibrational spectroscopy with simultaneous Raman and near-infrared absorption detection.

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Toward Dark Matter Searches with an Optical Highly Charged Ion Clock

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Optical atomic, ion, and molecular clocks represent a promising approach to the search for light dark matter and other physics beyond the Standard Model of particle physics. Clocks based on highly charged ions (HCIs, i.e. ionization states > 10) promise low susceptibility to external background fields and high sensitivity to variations in the fine-structure constant. The contribution presents several measurement and analysis techniques used in the context of the construction of an HCI clock at the Institute of Physics of Humboldt University of Berlin.

Growing ThF_4 crystals for an advanced solid state nuclear clock

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With the first nuclear clocks recently realized [1, 2], the search for dark matter in yet unprobed areas is quickly becoming a reality. To build such a timekeeping device a current approach is to embed Th-229 nuclei in CaF2 crystals. Whilst clock operation with these crystals already pushes the boundaries on dark matter searches, they suffer from inhomogeneous broadening caused by microstrain induced by doping. Therefore, the growth of crystals wherein the Th nucleus is natively incorporated into the crystal lattice is currently being developed. The work presented in this poster presentation highlights the current developments towards growing ThF4 crystals with the μ-PD method which are estimated to reduce the nuclear linewidth by up to a factor of 1000. This poster will include highlights of crystals currently in use, key challenges in the growth of next generation crystals, an overview of characteristics and VUV transmission of grown samples and an outlook on the potential performance of ThF4 crystals in a nuclear clock.

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Prospects for heterodyne detection of the Gertsenshtein effect

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The inverse Gertsenshtein effect converts a gravitational wave into electromagnetic radiation in a magnetic field, providing a mechanism for high-frequency gravitational wave detection. We develop a three-field formalism describing the joint dynamics of a gravitational wave, static magnetic field, and a coherent electromagnetic probe, identifying heterodyne cross terms at O(h) in the metric perturbation. We analyze the detection prospects for this signal in vacuum and their extension to resonant-cavity experiments.

Entanglement-enhanced quantum sensing for parity non-conservation in Ba^+

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Atomic parity non-conservation (PNC) is an exceptional probe for the low-energy regime of the electroweak theory [1]. It stems from the electron-nucleus neutral current interaction that weakly mixes the electromagnetic ground state $6^2S_{1/2}$ state with the $6^2P_{1/2}$ state, such that transitions to the metastable $5^2D_{3/2}$ can be bridged via both a small $E1_{pnc}$ and a larger E2 channel. Driving the E2($E1_{pnc}$) transitions simultaneously by placing the Ba^+ ion in the (anti)node of a cavity yields an interference term vectorial light shift of ~ 0.4 Hz from which $E1_{pnc}$ can be extracted [2]. In order to observe such a small effect, two Ba^+ ions are placed in a decoherence-free entangled state such that correlated noise is rejected, and coherence of on the order of the 80 s radiative lifetime can be reached, translating to a sub-10 mHz resolution. Moreover, in the absence of magnetic field gradients, the structure of the entangled state excludes all scalar light shifts, thereby isolating the PNC shift. Here, I will present the underlying physical principle and the progress towards building this Ba^+ quantum sensor.

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Hyperfine electronic bridge for the excitation of the isomeric state in ^{229}Th nucleus

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The ^{229}Th nuclear isomer serves as a promising platform for quantum metrology based on nuclear optical transitions. In addition to direct optical excitation, the electronic bridge (EB) mechanism provides an efficient alternative pathway for nuclear state manipulation. Previous studies have demonstrated that hyperfine interactions play a crucial role in two-photon EB processes in $^{229}Th^{3+}$ ions, achieving ultra-high fidelity isomeric population transfer via a STIRAP scheme [1]. However, by performing a full calculation that incorporates the complete hyperfine structure, we reveal that the hyperfine splitting in the isomeric $7p_{1/2}$ manifold significantly degrades the excitation probability by disrupting the two-photon resonance condition. To overcome this limitation, we propose to combine magic wavelength with quantum interference effects to effectively restoring high-fidelity isomeric excitation.

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