Searching for New Physics at the Quantum Technology Frontier

Sunday, 2 July 2023 - Friday, 7 July 2023

Congressi Stefano Franscini (CSF), Ascona (Ticino), Switzerland

Book of Abstracts

Contents

Quantum Sensors / 26

Antiprotonic atoms as a gateway system for BSM investigations

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Antiprotonic atoms have been produced since the 1980's, but recent developments of laser-controlled controlled charge exchange processes in Penning traps have opened up a wide range of new physics topics. This talk will address several of these, whose physics reach ranges from atomic cascades within antiprotonic Rydberg atoms, a new production method of trapped, cold, fully stripped radioisotopes, the formation of hydrogen-like Rydberg highly charged ions, the possibility of searching for a putative antiprotonic EDM in antiprotonic molecules, to a novel search for a heretofore unexplored dark matter candidate.

Atoms and Exotic Atoms II / 27

Fundamental Interactions and Beyond with X-ray Spectroscopy of Exotic Atoms

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Despite decades of effort, quantum electrodynamics (QED), the field theory that describes the interaction between light and charged particles, is poorly tested in the regime of strong coulomb fields. This is due to a confluence of difficulties linked to experimental limitations in highly-charged ion spectroscopy and nuclear uncertainties. I will present a new paradigm for probing higher-order QED effects using spectroscopy of Rydberg states in exotic atoms, where orders of magnitude stronger field strengths can be achieved while nuclear uncertainties may be neglected [1]. Such tests are now possible due to the advent of quantum sensing detectors and new facilities providing low-energy intense beams of exotic particles for precision physics. I will present first results from experiments with muonic atoms at J-PARC within the context of the HEATES collaboration, and discuss a new project for antiprotonic atom spectroscopy at CERN. Then, the paradigm can be flipped upside down, and the same quantum sensing detectors used specifically to look at fingerprint of nuclear properties in the atomic quantum structure. I will present the new QUARTET collaboration at the Paul Scherrer Institute which will make first precision measurements of charge radii in light nuclei starting in 2023 and may someday even be sensitive to beyond standard model physics [2].
[1] N. Paul et al, Physical Review Letters 126, 173001 (2021)
[2] A. Antognini et al, arXiv : 2210.16929 (2022)

Poster Session 2 / 29

GRASIAN: Towards the first demonstration of gravitational quantum states of atoms with a cryogenic hydrogen beam

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At very low energies, a light neutral particle above a horizontal surface can experience quantum reflection. The quantum reflection holds the particle against gravity and leads to gravitational quantum states (GQS). So far, GQS were only observed with neutrons as pioneered by Nesvizhevsky and his collaborators at ILL. However, the existence of GQS is predicted also for atoms.

The GRASIAN-collaboration pursues the first observation and studies of GQS of atomic hydrogen. We propose to use atoms in order to exploit the fact that orders of magnitude larger fluxes compared to those of neutrons are available. Moreover, recently the qBounce collaboration, performing GQS spectroscopy with neutrons, reported a discrepancy between theoretical calculations and experiment which deserves further investigations. For this purpose, we set up a cryogenic hydrogen beam at 6K. We report on our preliminary results, characterizing the hydrogen beam with pulsed laser ionization diagnostics at 243 nm.

Atoms and Exotic Atoms I / 30

Towards Improving the Precision of the Lamb Shift Measurement in Muonium

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Due to its lack of internal structure, Muonium is an excellent candidate to provide stringent tests for bound state QED. Furthermore, Muonium is a sensitive probe for the existence of exotic dark-sector particles, new muonic forces, and hidden dimensions. During the Mu-MASS [1] beamtime in December 2019 at the LEM beamline at PSI, we demonstrated the creation of an intense directed beam of metastable Muonium [2]. This opened up the possibility to measure the Muonium Lamb shift to an uncertainty of 2.5 MHz, which is an improvement of around an order of magnitude upon the last measurements [3]. Additionally, by measuring the isolated $2S_{1/2}, F = 0 \to 2P_{1/2}, F = 1$ transition for the first time [4], we demonstrated a promising way for an improved determination of the Muonium Lamb shift, provided that the measurement is not limited by statistics anymore. Towards reaching that goal, several improvements are envisioned at the LEM beamline to increase the muon and consequentially the metastable Muonium flux. The experimental setup, the current status and plans for future improvements will be presented.

[1] P. Crivelli, "The Mu-MASS (muonium laser spectroscopy) experiment", Hyperfine Interactions 239, 49 (2018)
[2] G. Janka et al., "Intense beam of metastable Muonium",Eur. Phys. J. C (2020)
[3] B. Ohayon, G. Janka et al., "Precision Measurement of the Lamb Shift in Muonium", Phys. Rev. Lett. 128, 011802 (2022)
[4] G. Janka et al., "Measurement of the transition frequency from $2S_{1/2}, F = 0$ to $2P_{1/2}, F = 1$ states in Muonium", Nat Commun 13, 7273 (2022).

Ions / 31

Searching for new physics with isotope-shift spectroscopy of trapped ions

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I will present recent results of a search for new physics using isotope-shift spectroscopy of Yb^+ ions at MIT [1,2], and plans for IS spectroscopy experiments in Ca^+ at ETH Zurich. Recently, IS spectroscopy of atoms and ions has been proposed as a method to search for a new force between the neutron and the electron, mediated by a hypothetical dark-matter-candidate boson in the intermediate mass range (100eV to 100keV) [3]. 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 (relating, for example, to small changes in the Coulomb potential of the nucleus 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.

In the Yb^+ search, conducted at the Vuletic group at MIT, we found the first evidence of King nonlinearity in a search for new physics [1]. In a subsequent paper, we established the observation of this nonlinearity with more than 41σ certainty [2]. With 4σ confidence, we found that the nonlinearity originated from at least two distinct physical effects: the dominant effect originated from differences in the fourth nuclear charge moment, a higher-order SM effect that had not previously been measured at this level of precision. The second source remains unexplained as, from atomic structure calculations, it likely cannot be fully accounted for by the expected next-largest SM effect.

In the TIQI group at ETH, we plan on continuing this search for new physics with spectroscopy of singly-ionized calcium, an element that offers smaller SM backgrounds, having been shown to exhibit no King nonlinearity up to 20Hz measurement precision [4]. Using an entanglement-enhanced spectroscopy technique that was previously demonstrated on Sr^+ ions [5], we plan to perform spectroscopy at 10mHz measurement precision, breaching current bounds on new physics.

[1] J. Hur, *D. P. L. Aude Craik* et al, PRL 128, 163201 (2022)
[2] I. Counts, *J. Hur* et al, PRL 125 123002 (2020)
[3] J. Berengut et al, PRL 120, 091801 (2018)
[4] C. Solaro et al, PRL 125 123003 (2020)
[5] T. Manovitz et al, PRL 123, 203001 (2019)

Interferometry / 32

Precise determination of the fine structure constant and test of QED

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Using an atom interferometer, it is possible to precisely measure the ratio between the Planck constant and the mass of an atom. This measurement allows improving the determination of the fine structure constant α. By using this value in the QED prediction of the magnetic moment of the electron, it is possible to precisely test the Standard Model. This test is particularly relevant as it is closely related to a similar test made on the muon that shows a discrepancy between theory and experiment.
In this talk, I will present how we have performed a measurement at the level à 80 ppt of α. I will also discuss the perspectives for improving the measurement and the recent development made on the experimental setup.

Atoms and Exotic Atoms I / 33

Challenging QED with atomic Hydrogen

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

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[4] A. Grinin et al., Science 370, 1061 (2020).

Atoms and Exotic Atoms II / 34

Searching for ultralight scalar dark matter with muonium and muonic atoms

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Ultralight scalar dark matter may induce apparent oscillations of the fundamental constants of nature and particle masses, including the muon mass. Oscillations in the muon mass may be directly probed

via temporal shifts in the spectra of muonium and muonic atoms. Existing datasets and ongoing spectroscopy measurements with muonium are capable of probing scalar-muon interactions that are up to 8 orders of magnitude feebler than astrophysical bounds. Ongoing free-fall experiments with muonium can probe forces associated with the exchange of virtual ultralight scalar bosons between muons and standard-model particles, offering up to 5 orders of magnitude improvement in sensitivity over complementary laboratory and astrophysical bounds.

References:
Yevgeny V. Stadnik, arXiv:2206.10808.
Y. V. Stadnik and V. V. Flambaum, PRL **114**, 161301 (2014); PRL **115**, 201301 (2015).

Atoms and Exotic Atoms II / **36**

1S-3S CW spectroscopy of Deuterium atoms

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I will present the 1S-3S spectroscopy campaign we carried on Deuterium atoms during the winter 2020, using our home-made CW 205 nm laser. After discussing some main systematics effects and a newly discovered one, affecting our beam-line, I will present the latest analysis results.

Molecules / **37**

Towards quantum control and spectroscopy of single hydrogen molecular ions

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The complexity and variety of molecules offer promising applications in metrology and quantum information that go beyond what is possible with atomic systems. We aim to study light molecular ions that are amongst the most fundamental and simplest molecules. Their internal structure can be calculated, making them prime candidates for the determination of fundamental constants as well as for theory benchmarks.
Spectroscopy of single ions is expected to reduce systematic uncertainties and improve signal strength. However, this requires quantum control over the spectroscopy ion, which can be achieved by co-trapping it with a well-controlled logic ion. Using the technique of quantum logic spectroscopy, it has been shown that even hard-to-control ion species can be prepared in a pure quantum state and measured non-destructively with high precision.
I will present our progress towards full quantum control of the hydrogen molecular ion H_2^+ and its reaction product H_3^+, each co-trapped with a beryllium ion in a linear Paul trap. We have demonstrated H_2^+ trapping times of up to 11^{+6}_{-3} hours, enabled by cryogenic pumping of background H_2 that suppresses chemical reactions converting H_2^+ to H_3^+. We have achieved ground-state cooling of

one of the motional modes of both H_2^+ and H_3^+, which is one of the first steps in many implementations of quantum logic spectroscopy. In addition, our cryogenic apparatus should allow for the use of buffer gas to cool the rovibration of molecular ions to their ground state.

Quantum Sensors II / 38

Quantum control of a levitated nanoparticle's motion to explore novel physics at large scales

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A nanosphere levitated in electromagnetic fields is a promising testbed for physics at the interface between the classical and the quantum realm. Recently, levitated particles have attracted attention as potential gravity *quantum* sources due to their large mass, ranging from 10^9 to 10^{12} amu. A prerequisite to test the quantization of the gravitation field is, however, to prepare the nanoparticle into a Schroedinger's cat, that is to place it in a superposition state of two different locations. To prepare this state, it is important first to reach a full quantum control on the levitated particle's motion.
When trapped in an optical tweezer, we manage to continuously measure its center of mass motion in a quantum-limited fashion. Building from this measurement, we exert feedback cooling to cool the nanoparticle motion along one direction close to the ground state of the trapping potential. The obtained state is closely described by a Gaussian wavefunction with a spatial extension of only 10 pm. To go beyond Gaussian states, one can exploit for instance the non-linear dynamics generated by the optical potential. Such a nonlinearity, however, becomes relevant at a length-scale dictated by the optical wavelength (~1 μm), five orders of magnitude larger than the initial wavefunction. To bridge this gap, we plan to expand the initial state by parametrically modulating the trapping stiffness. A combination of hybrid electro-optical trapping scheme, our optical measurement capability and a cryogenic environment should be capable of increasing the coherence time enough to expand the mechanical wavefunction by several orders of magnitude. I will show you our recent progresses towards this goal.

Poster Session 1 / 39

First antihydrogen production at the Gravitational Behaviour of Antihydrogen at Rest (GBAR) experiment and future prospects

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The upgrade of the antiproton decelerator, the Extra Low ENergy Antiproton (ELENA) ring started its operation at CERN in the Fall of 2021 and opened a new era for antihydrogen research. The Gravitational Behaviour of Antihydrogen at Rest (GBAR) collaboration has since started taking data and aims to directly test the Weak Equivalence Principle with a free fall of ultracold antihydrogen $\overline{\mathrm{H}}$ in Earth's gravitational field. The main principle is to first produce an antihydrogen ion $\overline{\mathrm{H}}^+$ and

sympathetically cool it with Be^+ in a Paul trap to $\mu\mathrm{K}$ temperature. The excess positron is then photodetached using a $1640\,\mathrm{nm}$ laser and the now neutral anti-atom experiences a classical free fall. By measuring the time of flight and the annihilation position of the $\overline{\mathrm{H}}$ we want to measure its acceleration with a precision of 1% in a first phase. During the production of the $\overline{\mathrm{H}}^+$, $\overline{\mathrm{H}}$ atoms, with a fraction in the 2S state, will be produced which can be used to measure the Lamb shift. I will present first evidence of $\overline{\mathrm{H}}$ production in 2022, a milestone for the experiment, as well as the status and future prospects of GBAR.

Interferometry / 40

Search for additional fundamental interactions using whispering gallery quantum states of neutral particles.

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The Standard Model of particle physics perfectly describes most of the observed phenomena, but leaves a number of problems unresolved, including the origin of the matter-antimatter asymmetry, the nature of dark matter, the absence of observed CP violation in the strong sector, the fine tuning needed for light Higgs. Most extensions of the Standard Model involve the introduction of new fundamental interactions in addition to the four known ones. Such interactions can be spin-independent or spin-dependent. An experimental search for such interactions is carried out by a wide range of methods, each of which has an optimal sensitivity in a certain range of characteristic distances. One such method is the precision measurement of the whispering gallery quantum states of neutral particles. Such states are analogous to the gravitational quantum states of neutral particles up to the replacement of the gravitational force by the effective centrifugal one. Neutron whispering gallery quantum states were observed and made it possible to provide a competitive constraint on extra interactions with a characteristic range of ˜10 nm. The advantage of the whispering gallery states is the fact that by choosing the mirror diameter and particle velocity, one can "fine-tune"the sensitivity of the experiment to the characteristic distance of the extra interaction. A further dramatic improvement in accuracy in experiments with neutrons is possible, but requires both a more accurate theoretical description of these states and a more precise characterization of the curved mirrors used for these experiments. One of the most precise methods for characterizing mirrors is to measure a related phenomenon: the whispering gallery of X-rays. Such measurements have been carried out and their results are currently being analyzed. Another potential method for increasing accuracy is to measure the quantum states of the whispering gallery of atoms; this method makes it possible to obtain a much higher statistical sensitivity, and the accuracy and reliability of the theoretical description of this phenomenon is of the same order as with neutrons. Experiments with atomic hydrogen are being prepared. Interesting additional possibilities are experiments with composite particles, including antiparticles (antihydrogen, muonium, positronium). Theoretical analysis of such systems continues. Separate parts of this scientific program will be presented in other reports at this conference, and research is carried out both within the framework of collaborations (GRASIAN, GBAR) and by individual scientists. Some progress in most of these areas is expected soon.

Quantum Sensors / 41

Search for dark matter with magnetic resonances

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Axionlike particles (ALPs) are candidates for dark matter that are strongly motivated by theory and are searched for in a plethora of experiments. At the Cosmic Axion Spin Precession Experiments (CASPEr) we exploit techniques based on nuclear magnetic resonance spectroscopy to probe possible non-gravitational couplings between dark matter and ordinary matter. This allows for sensitivity to ALPs over a large mass range, we currently aim to probe the range from 10^-22 eV up to 2.5 10^-6 eV. I will present our results obtained for various mass ranges and will discuss recent measurements at approximately 6 neV which are currently being analyzed. Attention will be paid to our work on the stochastic nature of the ALP field, daily and annual modulations, and gravitational lensing as well as methods to improve our sensitivity in future measurements.

Atoms and Exotic Atoms II / 42

Theory of light muonic atoms — Two-photon-exchange contributions to muonic hydrogen and deuterium

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I would like to discuss the theory of light muonic atoms, in particular, the two-photon-exchange polarizability contributions to the Lamb shift and hyperfine splitting in muonic hydrogen from baryon chiral perturbation theory and the two-photon-exchange contribution to the Lamb shift in muonic deuterium from pionless effective field theory. A focus will be on the ground-state hyperfine splitting in muonic hydrogen in view of future experiments.

Molecules / 44

Precision infrared molecular spectroscopy as an instrument for probing variations of fundamental constants

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Precision spectroscopy of dipole-forbidden rovibrational infrared transitions in molecular ions could serve as a probe for detecting possible temporal variation of fundamental constants and testing fundamental theories [1]. However, until recently, it was impossible to achieve the required precision due to the lack of control over the molecular ions on a single quantum level. We developed new methods which allow us to prepare a single molecular ion in its rovibrational ground state [2], detect its quantum state with high-fidelity [3] and perform highly sensitive and precise spectroscopic experiments on dipole-forbidden infrared transitions in N_2^+[4] driven by a quantum cascade laser [5]. The absolute frequency stability of the measurements is provided by referencing all laser frequencies to the Swiss primary frequency standard, the Cs atomic fountain clock FoCS-2, operated by the Swiss Federal Institute of Metrology METAS in Bern [6]. These will allow us to reach an absolute measurement precision level of 10^{-15}, establishing new state-of-the-art infrared spectroscopy of the molecular ions and approaching the boundary where BSM physics could be detected.

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Quantum Sensors / 45

Positronium physics in the quantum world

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Studies of the matter-antimatter system known as positronium are inherently quantum insofar as they involve an exotic atom that can decay into photons, and whose properties are for all practical purposes fully described by quantum electrodynamics. As a result, it is very easy to get involved in the new game of adding the word "quantum"to things that do not need or even deserve it. As such I will describe some microwave spectroscopy of Ps quantum states, possibly involving some kind of quantum technology. I will also discuss other quantum-like things we can do with positronium, such as gravity measurements using interferometric methods.

Poster Session 1 / 46

Precision spectroscopy of Muonium

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Muonium, the purely leptonic bound state of an anti-muon and an electron, is an excellent candidate to probe bound state QED and search for new physics beyond the Standard Model.
I will introduce Mu-MASS, aiming to improve the Muonium 1S-2S transition and Lamb Shift by orders of magnitude. I will present our latest experimental progress and results, with a special focus on the New Physics reach of the measurements, as well as up to date theoretical calculations for the transition frequencies.

Atoms and Exotic Atoms II / 47

Hydrogen, at MIT and UFRJ, and Antihydrogen Laser Spectroscopy, at the ALPHA collaboration at CERN

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I will discuss laser spectroscopy, particularly on the 1S-2S transition, of Hydrogen (H) and Antihydrogen (Hbar). The study of H recalls the work done at MIT in mid 90's and the setup under construction at UFRJ. The work with Hbar is done at the ALPHA collaboration at CERN. Details on line shapes, transition rates, detection schemes, will be discussed. The work has intimate connection to fundamental physics tests such as Charge-Parity-Time (CPT) symmetry, Quantum-Electrodynamics (QED), and Lattice-QCD tests as it is advancing towards predicting the proton charge radius.

Poster Session 2 / 48

Pulsed CW laser for long-term spectroscopic measurements at high power in deep-UV

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We present a novel technique for in-vacuum cavity-enhanced UV spectroscopy that allows nearly continuous measurements over several days, minimizing mirror degradation caused by high-power UV radiation. Our method relies on pulsing of the cavity's internal power, which increases the UV intensity to maximum only for short periods when the studied atom is within the cavity mode volume while keeping the average power low to prevent mirror degradation. Additionally, this method significantly decreases laser-induced background on charged particle detectors. The described 244 nm laser system is designed for 1S-2S two-photon CW spectroscopy of muonium in the Mu-MASS project. It was tested to provide intracavity powers above 20 W, requiring maintenance only a few times a day. The pulsing technique demonstrates minimal impact on the radiation frequency, with no observed shifts exceeding 15 kHz. Our approach represents a promising new technique for high-precision spectroscopy of atoms in harsh UV environments and demonstrates the feasibility of CW spectroscopy of muonium.

Atoms and Exotic Atoms I / 49

Muonic vs. electronic dark forces

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Precision atomic spectroscopy provides a solid model independent bound on
the existence of new dark forces among the atomic constituents. We focus on the keV-GeV region investigating the sensitivity to such dark sectors of the recent measurements on muonic atoms at PSI, muonium and positronium. To this end we develop for the first time, the effective field theory that describes the leading effect of a new (pseudo-)vector or a (pseudo-)scalar particle of any mass at atomic energies.

Atoms and Exotic Atoms II / 50

Precision spectroscopy of transitions from the metastable 2 ^{3}S$_1$ state of ^{4}He to high-\textit{n}p Rydberg states

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The metastable He ($(1s)^1(2s)^1$) atom in its singlet ($^1S_0$) or triplet ($^3S_1$) states is an ideal system to perform tests of ab-initio calculations of two-electron systems that include quantum-electrodynamics and nuclear finite-size effects. The recent determination of the ionization energy of the metastable $2\,^1S_0$ state of ^{4}He [1] confirmed a discrepancy between the latest theoretical values of the Lamb shifts in low-lying electronic states of triplet helium [2] and the measured $3\,^3D \leftarrow 2\,^3S$ [3] and $3\,^3D \leftarrow 2\,^3P$ [4] transition frequencies. This discrepancy could not be resolved in the latest calculations [5,6].

Currently, we focus on the development of a new experimental method for the determination of the ionization energy of the
$2\,^3S_1$ state of ^{4}He via the measurement of transitions from the $2\,^3S_1$ state to np Rydberg states. Extrapolation of the np series yields the ionization energy with sub-MHz accuracy.

In this talk, we present the progress in the development of our experimental setup, which involves (i) the preparation of a cold, supersonic expansion of helium atoms in the $2\,^3S_1$ state, (ii) the development and characterization of a laser system for driving the transitions to the np Rydberg states, and (iii) the implementation of a new sub-Doppler, background-free detection method. We present this new spectroscopic method, with which we cancel the ^{1}st-order Doppler shift and illustrate its power with a new determination of the ionisation energy of $2\,^3S_1$ metastable He.

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Quantum Sensors II / 51

Einstein-Podolsky-Rosen experiment with two Bose-Einstein condensates

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In 1935, Einstein, Podolsky, and Rosen (EPR) conceived a Gedankenexperiment which became a cornerstone of quantum technology and still challenges our understanding of reality and locality today. While the experiment has been realized with small quantum systems, a demonstration of the EPR paradox with massive many-particle systems remains an important challenge, as such systems are particularly closely tied to the concept of local realism in our everyday experience and may serve as probes for new physics at the quantum-to- classical transition. Here we report an EPR experiment with two spatially separated Bose-Einstein condensates, each containing about 700 rubidium atoms. Entanglement between the condensates results in strong correlations of their collective spins, allowing us to demonstrate the EPR paradox between them. Our results represent the first observation of the EPR paradox with spatially separated, massive many-particle systems. They show that the conflict between quantum mechanics and local realism does not disappear as the system size increases to more than a thousand massive particles. Furthermore, EPR entanglement in conjunction with

individual manipulation of the two condensates on the quantum level, as demonstrated here, constitutes an important resource for quantum metrology and information processing with many-particle systems.

Atoms and Exotic Atoms I / 52

Precision measurements of nk – 2s transition frequencies in the hydrogen atom

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Precision spectroscopic measurements in the hydrogen atom have a long tradition and extensive studies of transitions between states with principal quantum number $n \leq 12$ have been carried out [1-6]. These measurements can be used to determine values of the Rydberg constant and the proton charge radius [7]. We present a new experimental approach to perform measurements of transition frequencies between the metastable 2s $^2S_{1/2}(F = 0, 1)$ states of H and highly excited $n\,k$ Rydberg Stark states with principal quantum number $n \geq 20$.
\\We generate the hydrogen atoms by dissociating H_2 in a dielectric barrier discharge located at the orifice of a pulsed cryogenic valve [8]. The hydrogen atoms are entrained in the supersonic expansion of H_2. The atoms are photoexcited to a specific hyperfine level of the metastable 2s $^2S_{1/2}$ state by a home-built frequency-tripled Fourier-transform-limited pulsed titanium-sapphire laser (pulse length 40 ns) and enter a magnetically shielded region in which transitions to $n\,k$ Rydberg Stark states are induced by a narrow-band frequency-doubled continuous-wave titanium-sapphire laser, which is phase locked to an optically stabilized frequency comb and referenced over a fiber network to a SI traceable primary frequency standard [9]. The highly excited Rydberg states are detected by pulsed-field ionization. We present our measurement procedure and first results on the ($n = 20\,k = 0$) - 2s transition frequency.
This work was supported by the Swiss National Science Foundation through the Sinergia-Program (Grant No. CRSII5-183579) and Grant No. 200020B-200478.
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Quantum Sensors / 53

A cavity quantum electrodynamics implementation of the Sachdev–Ye–Kitaev model

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The search for a quantum theory of gravity has led to the discovery of quantum many-body systems that are dual to gravitational models with quantum properties. The perhaps most famous of these systems is the Sachdev–Ye–Kitaev (SYK) model. It features maximal scrambling of quantum information, and opens a potential inroad to experimentally investigating aspects of quantum gravity. A scalable laboratory realisation of this model, however, remains outstanding.
In this talk, I will discuss our proposal for a feasible implementation of the SYK model in cavity quantum electrodynamics platforms (cQED) [1]. I will motivate how driving a cloud of fermionic atoms trapped in a multi-mode optical cavity, and subjecting it to a spatially disordered AC-Stark shift, can realise an effective model which retrieves the physics of the SYK model, with random all-to-all interactions and fast scrambling.
Crucial to this endeavour are the ability to tune the number of cavity modes mediating the long-range interactions, as well as the size of the atomic cloud, as I will demonstrate at the hand of numeric simulations of the effective model's dynamics.
A further milestone in realising the above proposal, is the ability to introduce disorder into the cavity-mediated interactions in a controlled way.
I will discuss results from recent cQED experiments, which demonstrated this ability in the quantum simulation of disordered spin models [2].
Our work demonstrates the increasing capabilities of cQED quantum simulators, showing how these may be leveraged in the pursuit of studying quantum gravity in the lab.

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Electric Dipole Moments (EDMs) / 55

EDMcubed: Measuring the electron electric dipole matrix element using BaF molecules embedded in an argon matrix

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The EDM^3 collaboration is pursuing a measurement of the electric dipole moment of the electron using barium monofluoride molecules embedded in a cryogenic argon solid. The method allows for very large samples of molecules to be used and therefore very good statistical uncertainties can be expected. The scheme also shows promise for control of systematic uncertainties. An update on our studies of matrix-isolated BaF molecules will be presented.

Poster Session 1 / 56

Experiments with hydrogen atoms at ultra-low energies

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We present a recent progress towards experiments with hydrogen atoms at ultra-low temperatures, probing the ultra-low energy domain with the lightest and simplest of neutral atoms, which has served as a test probe of the fundamentals of physics throughout the era of modern physics. This work is a part of an international collaboration GRASIAN (Gravity, Spectroscopy and Interferometry with Atoms and Neutrons) [1].

Experiments will be carried out in a double-trap system. First we will accumulate and evaporatively cool H gas below 1 mK in a large Ioffe-Pritchard trap (IPT) recently built in Turku [2]. Then, the cloud of cold H will be transferred into a second, more shallow trap T_2 for further manipulation in the phase-space, aiming on reaching temperatures in the μK region for further experiments. We will release ultra-slow atoms from the trap onto the ideally flat surface of superfluid helium, from which their quantum reflection will lead to formation of gravitational quantum states (GQS) in the potential well created by the surface and Earth gravity. Precise measurements of the GQS energies will improve constraints on the existence of the unknown short-range forces between atoms and materials surface. Precision optical and microwave spectroscopy will be performed at the conditions when the atomic velocity related effects are eliminated, e.g. improving the accuracy of the 1S-2S interval. Bose-Einstein condensation of magnetically trapped gas will be re-visited and tried for H bound in the GQS. Our methods and results will be useful for experiments with antihydrogen pursued at CERN.

We report on the first experiments where we have demonstrated magnetic capture and confinement of H gas at temperature below 50 mK in our IPT. The loading of H into the sample cell (SC) was performed using a cryogenic H dissociator operating at 0.7 K followed by two stage thermal accommodators at 0.5 and 0.3 K feeding the gas into the SC. Measuring the heat released in recombination of atoms during and after the loading, we found that atomic flux of over 3×10^{13} atoms/s reaches the SC and $\sim 2 \times 10^{14}$ atoms are trapped at temperature of ~ 50 mK. At the next stage the trap T_2 will be assembled together with components necessary for the 1S-2S spectroscopy.

Electric Dipole Moments (EDMs) / 57

Search for the muon electric dipole moment using the frozen-spin technique.

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At the Paul Scherrer Institute we are developing a high precision instrument to measure the electric dipole moment (EDM) of the muon. The presence of a permanent EDM in an elementary particle would imply a violation of time invariance and the combined symmetry of Charge-Parity (CP). While the Standard Model of particle physics allows for a large CP-violating phase, it also predicts EDMs that are too small to be measured in the near future. However, many extensions to the Standard Model permit large CP-violating phases that could lead to large EDMs and, at the same time, potentially explain the observed baryon asymmetry of the Universe. Recent developments, such as the tensions in the magnetic anomaly of the muon and the electron, have made the search for a muon EDM a topic of particular interest.
The experiment at PSI will employ the frozen-spin method to suppress the anomalous precession of the muon spin, allowing for a sensitivity that cannot be achieved with conventional g-2 muon storage rings. With this technique, the expected statistical sensitivity for the EDM after one year

of data taking is 6×10^{-23} e·cm with the $p = 125$ MeV/c muon beam available at PSI. This work presents the muon EDM experiment at PSI, with a focus on the quantitative analysis of systematic effects that could mimic the EDM signal.

Quantum Sensors II / 58

Emergent pumping in a non-hermitian system

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The time evolution of an quantum system can be strongly affected by dissipation. Although this mainly implies that the system relaxes to a steady state, in some cases it can bring to the appearance of new phases and trigger emergent dynamics. In our experiment, we study a Bose- Einstein Condensate dispersively coupled to a high finesse resonator. The cavity is pumped via the atoms, such that the sum of the coupling beam(s) and the intracavity standing wave gives an optical lattice potential. When the dissipation and the coherent timescales are comparable, we find a regime of persistent oscillations where the cavity field does not reach a steady state. In this regime the atoms experience an optical lattice that periodically deforms itself, even without providing an external time dependent drive. Eventually, the dynamic lattice triggers a pumping mechanism. We will show complementary measurements of the light field and of the atomic transport, proving the connection between the emergent non-stationarity and the pump.

Quantum Sensors II / 59

Spin- and momentum-correlated atom pairs mediated by photon exchange

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Quantum gases coupled to high-finesse optical resonators are a versatile platform to simulate many-body quantum systems, offering a high degree of experimental control. All-to-all interactions between the atoms naturally arise in such systems from the coupling of the atoms to a cavity mode, while cavity leakage facilitates real-time access to the dynamics of this open quantum system.
Here, we report on the production of correlated atomic pairs in specific spin and momentum modes mediated by the exchange of cavity photons. Our implementation relies on Raman scattering between different spin levels of a spinor Bose-Einstein condensate, which is induced by the interplay of a running-wave transverse laser and the vacuum field of an optical cavity. Far-detuned from Raman resonance, a four-photon process gives rise to collectively enhanced spin-mixing dynamics. We investigate the statistics of the produced pairs and explore their non-classical character through noise correlations in momentum space. Our results offer prospects for quantum-enhanced sensing and for the quantum simulation of lattice gauge theories and quantum-information scrambling.

Poster Session 2 / 60

Interferometry setup for LEMING

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The LEMING experiment aims to test the equivalence principle for second generation matter, using a cold muonium beam (bound μ^+e^-), where the inertial mass is dominated by the muon.
The feasibility of such a measurement relies on measuring the gravitational deflection of a lifetime limited atomic beam.
The poster discusses the feasibility and developments towards using a Talbot-Lau atom interferometer for a percent level measurement of the gravitational constant in muonium.

Poster Session 1 / 61

Development of a cryogenic low threshold detector using perovskite nanocrystals

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The LEMING (LEptons in Muonium INteracting with Gravity) experiment aims to measure the gravitational acceleration of Muonium (M = e^- + μ^+) in the gravitational field of the earth. An essential part of this experiment is the reliable detection of M's decay products, i.e. e^+ and e^-, at temperatures below 1 K. The electron, referred to as atomic electron, can be accelerated to energies of $\mathcal{O}$(keV), thus requiring a sensitive detector. This work considers perovskite nanocrystals for the detection of the atomic electron. Preliminary tests at room and cryogenic temperatures are presented.

Molecules / 62

Searching for New Physics using hydrogen molecular ions (and more)

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Spectroscopy of the HD^+ molecular ion has made a ''quantum" leap in recent years, reaching part-per-trillion precision by use of techniques for Doppler-free excitation. The theoretical precision has also been improved, both in the spin-averaged transition frequencies and in hyperfine structure.

Under the assumption that the Standard Model correctly describes the physics of HD^+, comparison between theory and experiment can be used to improve the determination of the proton-electron

mass ratio. I will briefly describe a recent reanalysis of experimental data in the perspective of the adjustment of fundamental constants.

Using independent values of the particle masses deduced from Penning trap measurements, one can exploit HD^+ spectroscopy to constrain hypothetical interactions beyond the standard model. Here, a global approach to combine different types of spectroscopic data is desirable, keeping in mind that the vlaues of fundamental constants themselves could be affected by the New Physics being tested. I will present a self-consistent solution to this problem, and results of a first implementation of this method.

Ions / 63

Towards Ramsey-Comb Spectroscopy of the 1S-2S Transition in He+

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Precision spectroscopy of the 1S-2S transition in singly-ionized hydrogen-like helium is a promising avenue to test bound-state quantum electrodynamics. Additionally, combined with measurements on μHe^+ [1], nuclear size effects and the nuclear polarizability can be probed [2]. He^+ can be confined in a Paul trap and sympathetically cooled by laser-cooled Be^+, which also serves as the readout ion. Due to the strong binding of the remaining electron of He^+, the 1S-2S transition lies in the extreme ultraviolet (XUV) spectral range. We aim to measure this transition with 1 kHz or better accuracy using Ramsey-comb spectroscopy (RCS) [3], combined with high-harmonic generation (HHG) [4].

In RCS, two pulses (near 790 nm) from a frequency comb (FC) pulse train are selectively amplified to the mJ-level, upconverted to the XUV via HHG, and then used to do a Ramsey-type measurement by slightly scanning the repetition frequency of the FC. This is repeated for different pairs of (amplified) pulses of the FC, at different macro-delays that are equal to an integer times the repetition time of the FC. By combining Ramsey fringes measured at different macro-delays, we restore most of the good properties of the FC, almost as if the whole pulse train was employed for the excitation. An important difference with direct FC spectroscopy is that phase shifts which are constant for all fringes drop out of the analysis [5]. This includes the phase shifts from amplification, HHG, and the ac-Stark shift of the transition. Moreover, for a trapped He^+ ion, it will enable us to cancel the first-order Doppler shift by synchronizing the repetition frequency of the comb to the secular frequency of the helium ion. As a result, Doppler-free excitation will become possible with unequal photons, one at 790 nm, and one at its 25^{th} harmonic (32 nm), which strongly enhances the excitation probability compared excitation with 2 times 60 nm.

We now demonstrate an important step towards this goal with the first laser excitation of the 1S-2S transition in He+, based on an atomic beam of helium. Within a single 150 fs laser pulse, helium atoms are first ionized to He^+, then excited from the 1S to the 2S state (in He^+), and finally the He^+ ions in the 2S state are ionized again to He^{2+}. By scanning the central wavelength of our frequency comb laser, we can observe the 1S-2S resonance with the He^{2+} signal. We can independently vary the XUV and 790 nm intensity, and show that the observed ac-Stark shifts are consistent with the expected values and are compatible with RCS. This paves the way to high-precision 1S-2S laser spectroscopy of He^+ in an ion trap with Ramsey-Comb spectroscopy.

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Ions / 64

Penning trap precision experiments for fundamental physics

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Experiments with single ions confined in a Penning trap enable access to a broad range of observables that are of fundamental importance for our understanding of fundamental physics. In the magnetic field of the trap, the cyclotron frequency of an ion can be determined with unique precision and gives direct access to the charge-to-mass ratio. Furthermore, we have access to the gyromagnetic g-factor via a measurement of the (Larmor) spin precession frequency. This way, we have determined a number of fundamental parameters, such as the electron, proton, neutron and deuteron atomic masses with leading precision.
This way, in our new generation experiment ALPHATRAP we have recently measured the g-factor of highly charged, hydrogenlike ^{118}Sn. A comparison to a precise prediction by quantum electrodynamics (QED) allows probing the validity of QED in extreme electric fields, in the order of 10^{15} V/cm.
Furthermore, by crystallizing two ions simultaneously in one trap we have achieved a leap of two orders of magnitude on the precision frontier. With this new technique, we have recently determined the isotopic effect of the g-factor in hydrogenlike neon ions, at 13 digits precision with respect to g and are consequently sensitive to previously invisible contributions, such as the QED recoil, and can set limits on hypothetical new physics such as dark matter mediated couplings.
Currently, we are designing a novel experiment that will allow storing a single positron and cooling it to the ground state of motion. Then, using a similar technique will enable comparing the spin precession of electron and positron with 14 digits precision, which would yield a very stringent test of CPT in the lepton sector.
Finally, the possibility to determine the internal state of a single ion gives us access to systems that were previously difficult to handle, such as the molecular hydrogen ions. Currently, we are performing spectroscopy on HD^+ and soon H_2^+. The development of the necessary toolbox will be a seminal step towards a possible future spectroscopy of the antimatter equivalent, $\bar{H}_2^-$, which will enable a unique test of charge-parity-time (CPT) reversal symmetry.

Poster Session 1 / 65

Sympathetic cooling of charged particles in separate Penning traps

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The observed matter-antimatter asymmetry in the universe has yet to be understood. The experiments of the BASE Collaboration are dedicated to rigorous tests of the fundamental CPT symmetry in order to tackle this mystery. For this purpose, BASE compares the properties of the proton and the antiproton with highest accuracy, specifically the magnetic moments/g-factors [1,2] and the charge-to-mass ratios [3]. Cooling the proton and antiproton has been a limitation in previous measurements. Deterministically reaching the 10 mK range on short interaction time scales will considerably increase the sampling rate and boost the fractional accuracy that is reached in our experiment.

Direct laser cooling of ions gives access to the mK range or even beyond, and it is the method of choice in many precision experiments. In our case, a suitable laser cooling transition is missing. We recently demonstrated an alternative and novel approach by sympathetically cooling a single proton via induced image currents of a laser-cooled Be+ cloud located in a separate trap [4]. This concept is highly promising, because it allows to cool any kind of charged particles, including molecules, highly charged ions, and importantly charged particles of opposite charge such as the antiproton.

This contribution will summarize our previous work [4,5] and report on recent progress and results.

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Quantum Sensors II / 66

Frequency-based decay electron spectroscopy to measure neutrino mass and exotic interactions

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Precision measurements of $\beta-$decay spectra can provide exquisitely sensitive tests of various predictions and underlying symmetry assumptions of the Standard Model (SM) of Particle Physics. Hypothetical scalar- and tensor-type interactions can alter the shape of the $\beta-$decay spectrum across the full energy range, while the finite masses of neutrinos mostly alter its shape around the decay endpoint in a predictable but yet undetectable way.
Novel electron spectroscopy technologies are required to push the currently achievable sensitivity limits to new frontiers. One such technique, Cyclotron Radiation Emission Spectroscopy (CRES), determines the kinetic energy from the frequency of the feeble cyclotron radiation emitted by single decay electrons spiraling in a magnetic trap.

In a first step to design an experiment with a sensitivity of $40\,\mathrm{meV/c^2}$ to the neutrino mass scale, the Project 8 collaboration has recently measured the first frequency-based limit on the neutrino mass $\left(\leq\ 155\,\mathrm{eV/c^2}\right)$ based on CRES with molecular tritium.
In a small volume experiment the excellent energy resolution was demonstrated with conversion electrons from $^{83}\mathrm{Kr}$ and no background event beyond the tritium decay endpoint was observed.

I will discuss this result and the identified R\&D plan including quantum sensor technology to investigate the path to sensitivity reaching down to the inverted mass ordering scheme of neutrino masses.

CRES has recently also been successfully demonstrated for MeV-electrons and -positrons within the He6-CRES collaboration using ^{6}He and ^{19}Ne. This establishes CRES as a novel non-demolition frequency-based technology from the mildly to the highly relativistic energy range of electrons emitted in nuclear $\beta-$decays.

The work has been supported by the Cluster of Excellence "Precision Physics, Fundamental Interactions, and Structure of Matter"(PRISMA+ EXC 2118/1) funded by the German Research Foundation (DFG) within the German Excellence Strategy (Project ID 39083149), the U.S. Department of Energy Office of Science, Office of Nuclear Physics, the National Science Foundation, and by internal investments at all collaborating institutions.

Quantum Sensors II / 67

Neutron Beam EDM and Axion-Like Dark Matter

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The neutron represents a versatile tool in the realm of fundamental particle physics. It is used to perform precision physics measurements at low energies with the goal to search for beyond Standard Model signals. In this presentation, we will introduce activities currently pursued at the University of Bern. The projects encompass the hunt for a CP-violating neutron electric dipole moment using a pulsed beam and the search for a so-far undetected hypothetical axion-like particle as possible dark-matter candidate.

Interferometry / 68

Measuring the Charge of the Neutron using a Time-Of-Flight Neutron Grating Interferometer

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The present best direct limit on the neutron electric charge is $(-0.4 + -1.1)10^{-}21$ e and was measured in a precision experiment by Baumann and colleagues in the 1980's [1]. In Bern we are pursuing the QNeutron project which investigates an innovative technique to measure ultra-small angle neutron beam deflections. The experimental apparatus consists of a symmetric Talbot-Lau type neutron interferometer with three absorption gratings operated in time-of-flight mode. Ultimately, the instrument shall allow to detect neutron beam deflections, e.g. due to an applied electric field, on the picometer scale. A full-scale experiment could lead to a statistical improvement of the neutron electric charge sensitivity by up to two orders of magnitude [2]. So far, several successful measurements have been performed with a prototype setup where deflections on the nanometer scale could be resolved. In this talk, we will present the fundamental idea, first results and challenges of this endeavor.

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Poster Session 1 / 69

The LUXE experiment and the new physics search with optical dump NPOD

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The LUXE experiment at the DESY in Hamburg (DE) will study strong-field quantum electrodynamics in the interactions of a beam of electrons or photons with a high-intensity laser. New electrons, positrons, and photons can be created in Compton and Breit-Wheeler processes. The main objective of LUXE is to measure the laser intensity dependence of the matter-antimatter pair production rate. Additionally, the photons produced in the primary interactions can be directed to a beam dump to search for axion-like particles (ALPs).

Quantum Sensors / 70

New Technologies for Dark Matter Detection

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The exploration of dark matter beyond the standard lore is of vital importance towards resolving the identity of dark matter. I will discuss new proposals for the direct detection of light dark matter which hold much promise. These include the use of superconducting nanowires, two-dimensional targets such as graphene, and heavy fermion materials. Considering dark matter interactions with these targets, I will demonstrate the potential of the light dark matter direct detection program in upcoming years.

Quantum Sensors II / 71

Low-threshold detectors for dilution refrigerators

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The LEMING experiment aims to test weak equivalence in leptonic antimatter. We will employ atomic interferometry to measure the vertical deviation of a horizontal cold muonium beam. Generation of cold muonium requires the experiment to operate well below 1K. Therefore, particle detectors operating reliably at these temperatures are crucial. We have successfully achieved sub-kelvin operation of commercial silicon photomultipliers (SiPMs). Furthermore, a strong background suppression is required in order to reach the intended sensitivity. This can be achieved via a reliable detection of the atomic electron from the muonium, left over after the decay of the muon. However,

these electrons possess very low energies. Hence, a second detector is required which not only operates below 1K, but also features an energy detection threshold below 1keV. This talk will focus on our sub-kelvin characterisation of commercial SiPMs as well as several low-threshold technologies we are investigating, including superconducting nanowires and perovskite scintillators.

Molecules / **72**

Radioactive Molecules as Quantum Sensors for Fundamental Physics

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Recent advances in precise control and study of molecules have opened up new opportunities for fundamental physics research. Radioactive molecules, in particular, can be artificially created to contain nuclei with extreme proton-to-neutron ratios, providing an extreme sensitivity to symmetry-violating nuclear properties. Precision measurements of these systems can offer unique and complementary laboratories in our search for new physics. In this talk, I will present recent highlights and perspectives from laser spectroscopy experiments on these exotic species.

Poster Session 2 / **73**

Novel production method of a cold muonium beam

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Muonium ($M = \mu^+ + e^-$) is a purely leptonic exotic atom which can be used as an unique probe for New Physics through precision spectroscopy measurements or through a gravity measurement testing the weak equivalence principle on elementary antimatter. We are developing a novel M source based on stopping accelerator muons in a layer of superfluid helium at cryogenic temperatures.

In this contribution results from the first observation of M emitted from superfluid helium are presented. An initial characterization of the novel M source shows the fast diffusion of M atoms in the superfluid resulting in a vacuum M yield comparable to standard M sources, which use low energy muons only available at much lower muon intensities. The emitted M atoms showed an sub-thermal behaviour with a high velocity and a directed emission. Prospects of this newly developed high intensity, low emittance atomic M beam from superfluid helium in the context of a free fall experiment of M will be discussed.

Poster Session 1 / **74**

muCool: High brightness ultra-cold positive muon beam

Authors: Joanna Peszka[1]; Aldo Antognini[2]; Ryoto Iwai[3]; Giuseppe Lospalluto[None]; Klaus Stefan Kirch[None]; Patrick Mullan[1]; Mikio Sakurai[4]; David Taqqu[None]; Taylor Yan[None]; Malte Hildebrandt[None]; Andreas Knecht[None]; Jonas Nuber[None]; Angela Papa[None]; Claude Petitjean[5]; Bastiano Vitali[None]

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The muCool project aims to develop an innovative device for generating low-energy, high-intensity, and high-quality muon beams for future high-precision experiments such as muon g-2 measurements, muonium spectroscopy, and muonium gravity studies. These experiments, involving muons and muonium atoms, hold significant potential for testing theoretical predictions of the Standard Model within a purely leptonic system.

The muCool device is designed to reduce the phase space of a standard μ^+ beam by a factor of 10^{10} with an efficiency of 10^{-3} [1]. The muCool device is a cryogenic helium gas target with a complex electric field geometry inside the active volume, placed in a homogeneous magnetic field of $5\ T$. Muons are transversely compressed by a combination of $E \times B$ drift and drift resulting from collisions with helium gas, as the collision frequency changes vertically due to the gas density gradient. Longitudinal compression is achieved through an electric potential minimum along the length of the muCool device. Combined transverse and longitudinal compression of the muon beam to sub-millimeter size and cooling to eV energies have been demonstrated recently [2]. To make the muCool device compatible with future muon experiments, the muon beam must be extracted from the target volume through an orifice. The extraction step poses a significant technical challenge in maintaining the helium gas density profile inside the muCool target while transitioning from a closed to open volume design. The upgraded design concept and simulation results for muon beam extraction will be presented.

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Ions / **75**

New measurement of the electron magnetic moment

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A single isolated electron in a Penning trap yields a new measurement of the electron magnetic moment g/2 = 1.001 159 652 180 59 (13).
A comparison of the measured g-factor and the predicted g-factor using an independent measurement of the fine structure constant provides the most stringent test of the Standard Model.
The newly constructed system used for this measurement which resulted in increased stability and a better understanding of systematic errors, along with efforts towards a further improved measurement using new techniques, will be discussed.

A new limit on dark photon dark matter at 0.6 meV is also obtained using the same system.
The single trapped electron is used as a background-free detector at 0.6 meV.
The search demonstrates the sensitivity of the single electron to the dark photon in the 0.1–1 meV range.

Electric Dipole Moments (EDMs) / 76

Next-generation nEDM search at PSI

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The next-generation neutron electron dipole moment (EDM) measurement is currently under construction at the Paul Scherrer Institute (PSI), the n2EDM experiment. n2EDM will deliver, at minimum, an order of magnitude better sensitivity as compared to current limits on the neutron EDM. This increased sensitivity on the neutron EDM will provide stringent constraints on time-reversal violating processes and deeply probe physics beyond the Standard Model (BSM).

In this talk, I will present the current status of the experiment, characterizations of critical components, and outline the near future for n2EDM. Furthermore, I will discuss plans to explore quantum systems to improve systematics for a future measurement.

Electric Dipole Moments (EDMs) / 77

Systematic effects in searches for the electron EDM

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Experimental searches for permanent electric dipole moments (EDM) on a fundamental particle are predominantly executed in composed systems, such as neutrons, atoms or molecules. The experiments have reached a sensitivity which narrows the gap to the Standard Model predictions significantly which requires an improved understanding of the properties of composed systems in a particular experimental implementation. The NL-eEDM collaboration has built an experiment which employs a molecular beam of barium-monofluoride (BaF) [1]. We will discuss the measurement process of spin-precession in external electric and magnetic fields [2]. The method provides a path to the reduction of a systematic bias to an eEDM, in particular to the applied external electric field.

[1] P. Aggarwal et al., Measuring the electric dipole moment of the electron in BaF, Eur. Phys. J. D 72, 197 (2018)

[2] A. Boeschoten et al., Novel spin-precession method for sensitive EDM searches, arXiv:2303.06402 [physics.atom-ph], (2023)

Quantum Sensors / 82

QUAX: Probing Axion Dark Matter through quantum technologies

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The QUest for Axion (QUAX) is a direct-detection CDM axion search which reaches the sensitivity necessary for the detection of galactic QCD-axion in the range of frequency 8.5-11 GHz.

The QUAX collaboration is operating two haloscopes, located at Padova/LNL- and LNF-INFN laboratories in Italy, that work in synergy and operate in different mass ranges.

In this talk we will report about results obtained at the Padova-LNL laboratories , using a high quality factor dielectric cavity cooled at less than 100 mK inside a dilution refrigerator equipped with a 8 T magnet with a JPA and TWPA-based amplification chain for cavity signal readout, resulting in a system noise temperature at the quantum limit.

Results will presented for the axion-electron and axion-photon coupling around the 10 GHz frequency range.

We will also report about R&D activity aimed at increasing the scanning speed with application of transmon-based single microwave photon detectors (SMPDs) for cavity readout.

The prototype haloscope we developed is based on a cylindrical copper cavity sputtered with NbTi, resonant at 7.3 GHz frequency, and cooled at mK temperatures inside a dilution refrigerator equipped with a SC magnet.

Results obtained employing a moderate magnetic field will be described.

Poster Session 2 / 83

Magnetometry with laser-cooled beryllium ions in ALPHA Antihydrogen Experiment

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In the ALPHA Experiment, laser-cooling of beryllium ions has been introduced to sympathetically cool positrons [1], which is anticipated to increase antihydrogen production [2]. Beryllium ions are generated through Pulsed Laser Ablation [3] and are trapped in the same Penning-Malmberg trap utilized for trapping and preparing antiproton and positron plasmas for antihydrogen synthesis. Cold beryllium ions may be employed for in-situ measurements of magnetic fields in the ALPHA antihydrogen traps. Magnetometry is critical for trapped antihydrogen research, particularly for antimatter gravity measurements conducted at high magnetic fields. As the precision of antihydrogen spectroscopy measurements increases, the uncertainty of the magnetic field will contribute more to systematic errors. Beryllium ion magnetometry presents a promising alternative to the currently used Electron Cyclotron Resonance (ECR) technique [4] and it requires no major hardware upgrades to the ALPHA apparatus.

The proposed method involves measuring an electron spin-flip transition frequency in the ground state of $^9Be^+$, which is highly sensitive to external magnetic field strength. The electron spin-flip transition can be induced by microwave radiation in a Rabi-style experiment and detected through fluorescence from a laser-cooling transition, analogous to an experiment performed at NIST with beryllium ions confined in a Penning trap [5]. An additional advantage of utilizing electron spin-flip in Be^+ is its capability to characterize the strength of the microwave field within the ALPHA-2 trap. Microwaves are used in ALPHA Experiment to drive the ground-state hyperfine transition of the antihydrogen (positron spin-flip) [6] and the intensity of microwave field is known to vary inside the the ALPHA-2 Penning trap. Previously, estimates of microwave intensity inside the trap were determined using the ECR technique, which is sensitive to the microwave electric field component. Both positron spin-flip in antihydrogen and electron spin-flip in $^9Be^+$ are magnetic dipole transitions, enabling beryllium ions to characterize the magnetic field component of microwaves, which would enhance the measurement of hyperfine splitting in antihydrogen.

For the first time within the ALPHA apparatus, microwave-induced electron spin-flip in Be^+ was observed. The precision of the external magnetic field measurement derived from this proof-of-principle study was comparable to the currently used Electron Cyclotron Resonance method, and there is potential for significant improvement.

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Ions / **84**

Quantum logic and precision measurements with atoms and molecules

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The extreme precision and accuracy of state-of-the-art optical atomic clocks can be used to look for very small deviations from the predictions of the Standard Model, offering a tool to search for beyond Standard Model (BSM) physics complementary to particle accelerators. These searches are based on measuring the frequency ratio of two transitions that depend differently on interactions with BSM particles or fields. In this talk, I will present frequency ratio measurements between atomic clocks based on Al+, Hg+, Sr, and Yb atoms at NIST and JILA in Boulder, Colorado, and the use of these measurements to constrain the coupling of ultralight scalar dark matter candidates to the Standard Model particles and fields. Next, I will describe how the quantum-logic spectroscopy techniques first developed for Al+ clocks have enabled quantum control and precision measurements of molecular ions, with a variety of applications. Finally, I will conclude with a brief discussion of new experiments being set up at UCLA in Los Angeles, California based on different atomic, molecular, and nuclear transitions with much higher sensitivity to BSM physics in a variety of sectors.

Atoms and Exotic Atoms I / **85**

Precision benchmarks for nuclear and atomic physics from laser spectroscopy of muonic atoms

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Laser spectroscopy of muonic atoms, hydrogen-like atoms formed by a negative muon and a nucleus, has recently provided the charge radii of the lightest nuclei (proton, deuteron, 3He and 4He) with unprecedented accuracy. In this talk we present laser spectroscopy of these exotic atoms and their contribution to nuclear physics. Emphasis will be given to the new results in 3He.

Moreover we will emphasise how these measurements are impacting the determination of fundamental constants leading to the best tests of atomic and molecular energy levels for few-body systems such as H, He, H2+ and H2 providing the best verification of Quantum Electrodynamics for bound systems.

Electric Dipole Moments (EDMs) / 86

Electric dipole moments in effective field theory

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The baryon asymmetry of the universe points towards CP-violating sources beyond the Standard Model. If these consist of heavy new particles, their indirect low-energy effects can be described by effective field theories. I will describe theoretical challenges and recent progress within this framework for the extraction of bounds on CP violation, focusing on hadronic EDMs. In particular, I will discuss the connection to lattice-QCD as an input for non-perturbative matrix elements.

Interferometry / 87

Dark matter searches with AION-10 and beyond

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In this talk, I will introduce AION, a multi-stage atom interferometer project that aims to detect ultra-light dark matter candidates. The first stage, AION-10, will stand 10m tall in a stairwell in the Physics Department in the University of Oxford. AION-10 will operate in a gradiometer configuration, which means that two identical atom interferometers are run simultaneously, launching from the bottom and middle of the baseline. I will present near- and long-term sensitivity projections for several ultra-light dark matter candidates. I will also discuss potential backgrounds from anthropogenic and seismic noise, as well as possible mitigation strategies.

Atoms and Exotic Atoms I / 88

Testing fundamental interactions with the hyperfine splitting in light atomic systems

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While electrons are point-like particles, atomic nuclei have an intricate internal structure. Modern atomic and molecular calculations typically neglect this nuclear structure and represent the nuclei through the static charge and magnetic-moment distributions. There are, however, a number of important fundamental questions for which we do not have fully satisfactory answers yet: Is the description of composite nuclei by the elastic form factors physically adequate? What is the significance of inelastic multi-photon exchange effects? How can we account for the finite-nuclear mass effects of a composite nucleus in atomic systems? Several important discrepancies have been reported in the literature in recent years, that cannot be explained within the existing paradigms of quantum electrodynamics, specifically for the hyperfine splitting of the muonic deuterium, of the HD+ molecule, and of the lithium atom.

I will present overview of the hyperfine structure theory and possible resolution of reported discrepancies.

Interferometry / 89

Exploring dark matter and quantum space-time fluctuations through precision laser interferometry

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In this talk, I present a novel approach based on precision laser interferometry that combines the search for axion-like particles and low-mass scalar-field dark matter with the investigation of quantum space-time fluctuations. For the dark matter search, our method employs polarimetry with a Fabry-Perot cavity in combination with high birefringence crystals to achieve unprecedented sensitivity across a wide spectrum of potential dark matter particle masses. Additionally, I will discuss our experimental efforts to test quantum space-time fluctuations, which stem from the holographic principle and aim to unify quantum field theory and general relativity. Our integrated approach represents a significant advancement in dark matter searches and quantum gravity detection, offering new insights into fundamental physics. The precision of laser interferometry plays a crucial role in enabling these novel experiments by providing state-of-the-art measurements.

Poster Session 1 / 91

Searching for Physics beyond the Standard Model using Antiprotons at BASE

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The Baryon Antibaryon Symmetry Experiment (BASE) at the antiproton decelerator of CERN is dedicated to high-precision measurements of the fundamental properties of the proton and the antiproton. Using single-particle multi-Penning-trap techniques, we compare the proton/antiproton charge-to-mass ratios [1] and magnetic moments [2,3] at a relative uncertainty at the 10-parts-per-trillion and parts-per-billion level respectively. Such experiments provide stringent tests of Lorentz and CPT invariance in the baryon sector.

Our measurement campaigns typically span several months up to more than one year. Besides comparing static fundamental properties, we can apply time-based analysis methods to our data and gain sensitivity to additional effects beyond the Standard Model. Signatures of different types of Lorentz violation (with and without CPT violation) appear as signals at harmonics of the sidereal frequency [4]. A difference in gravitational coupling to protons and antiprotons would induce an annual variation of their charge-to-mass ratios, providing a test of the weak equivalence principle for clocks [1]. Moreover, a CPT-violating interaction of antimatter with ultralight scalar dark matter would induce oscillations of the measured antiproton mass. In this contribution, I will present the results

of our search for new physics using the time-based re-analysis of our latest antiproton-to-proton charge-to-mass ratio campaign.

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[3] G. Schneider et al., Science 358, 1081 (2017).
[4] Y. Ding and V. A. Kostelecký, Phys. Rev. D 94, 056008 (2016).

Poster Session 2 / 92

Shuttling and merging of mixed-species ion chains

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I will describe work performed on a Paul trap where we have demonstrated splitting and merging of mixed-species ion chains containing beryllium and calcium ions. These have a large mass ratio of > 4, which presents a number of complications, including decoupling of motional modes and large differences in mode frequencies, which primarily result from the difference in pseudo potential confinement arising from the radio-frequency trapping fields. We have recently investigated and overcome a number of problems arising from these, and demonstrated the splitting of two-ion Ca-Be chains with only a few quanta of motional excitation. Although these species were chosen for quantum information purposes, the methods are relevant to re-configuration of ion chains of other species, which may be of relevance for spectroscopy of exotic species using quantum logic spectroscopy.
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Atoms and Exotic Atoms II / 93

Probing Nuclear Sizes through Precision Spectroscopy of Ultracold Bosonic and Fermionic Helium

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Precision measurements on calculable systems are commonly used for tests of highly involved quantum electrodynamics (QED) calculations and are sensitive probes for the discovery of new and unexplored areas of physics. In our experiment we apply laser cooling and trapping techniques on helium atoms, to perform a highly accurate measurement on the doubly forbidden 23S1 −21S0 transition at 1557 nm. From the isotope shift of this transition between the bosonic 4He and fermionic 3He isotope we extract the squared charge radius difference between the nuclei, which is used as a benchmark for tests of QED and comparison with muonic systems.

Our most recent experiment involves the measurement of this transition in a degenerate Fermi Gas of 3He, confined in a dipole trap at the 319.8 nm magic wavelength. In this configuration, the spectral lineshape is purely dominated by the Fermi-Dirac statistics of the gas, and showcases a remarkable sub-Doppler narrowing effect due to Pauli blockade of stimulated emission in the dense part of the cloud. Our modeling and tests of this unexpected effect confirm the first observation of Pauli blockade in a coherently driven system. [1]

The resulting accuracy of the 3He transition itself sets a solid benchmark for electronic structure calculations, as does a precise evaluation of the magic wavelength condition. We combine this newest result with our earlier measurement on a 4He Bose-Einstein condensate [2] to obtain the isotope shift. Together, this provides the most accurate determination of the nuclear charge radius difference between the alpha and helion particle, which defines a strong benchmark for tests of fundamental physics.

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Poster Session 2 / 94

Towards Improving the Precision of the Negative Muon Mass via Muonic Helium HFS Spectroscopy

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uonic helium is a hydrogen-like atom composed of a helium atom with one of its electrons replaced by a negative muon. Its ground-state hyperfine structure (HFS), resulting from the interaction of the remaining electron and the negative muon magnetic moment, is very similar to muonium but inverted. High-precision measurements of the muonium ground-state HFS interval are recognized as the most sensitive tool for testing bound-state quantum electrodynamics (QED) theory [1] and also determining fundamental constants of the positive muon magnetic moment and mass. New precise measurements are now in progress by the MuSEUM collaboration at J-PARC [2]. The same microwave magnetic resonance method can also be used to precisely determine the muonic helium atom HFS interval and the negative muon magnetic moment and mass. The world's most intense pulsed negative muon beam at J-PARC MUSE allows for improving previous measurements and testing further CPT invariance by comparing the magnetic moments and masses of positive and negative muons (second-generation leptons), where an improvement by a factor of 50 or more is possible [3]. Also, a more precise determination of the muonic helium atom HFS interval will be beneficial to test and improve the theory of the three-body atomic system.

Already, measurements at MUSE D-line were performed utilizing the MuSEUM apparatus at zero field. Muonic helium atom HFS were measured at three different gas pressures to determine the HFS interval at zero pressure using methane as an electron donor to form neutral muonic helium atoms. The data analysis was just completed, and the accuracy obtained of 4.5 ppm is already better than both previous measurements [4,5]. Furthermore, a new experimental approach to recover the muon polarization lost during the muon cascade process is being investigated by repolarizing muonic helium atoms using a spin-exchange optical pumping (SEOP) technique [6]. The first laser repolarization experiment was recently performed. Finally, the preparation for high-field measurements at H-line is in progress, which will allow for improving the negative muon mass. An overview of the different features of these new muonic helium atom HFS measurements and the latest results will be presented.

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Poster Session 2 / 95

Dressed spin states of protons in water

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The Jaynes-Cummings model describes the system of a two-level atom which is interacting with a photon field in a quantum-mechanical framework. We present a Rabi-type experiment that tests this model. Our system comprises the nuclear spin of protons in water and an oscillating magnetic field. We measured the spin-state transition with various numbers of electromagnetic-field quanta involved.

Atoms and Exotic Atoms I / 96

Introduction to the session

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Interferometry / 97

Techniques for testing of antimatter gravity by Rydberg-positronium interferometry

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The most precise measurements of the acceleration due to gravity, g, of atoms are performed using the techniques of atom interferometry [1]. In general these approaches rely on the preparation of translationally cold samples of ground-state atoms and are therefore at present challenging to implement for tests of the Weak Equivalence Principle (WEP) with neutral antimatter - in particular positronium with its short ground-state annihilation lifetime of 142 ns. To address these challenges, we have developed a method to perform atom interferometry with samples in high Rydberg states [2,3]. This is an electric analogue of magnetic Stern-Gerlach interferometry [4]. In this approach, we prepare atoms in coherent superpositions of Rydberg states with different static electric dipole moments - or Stark shifts - and use inhomogeneous electric fields to apply state-dependent forces on them. This leads to the coherent generation of spatially separated atomic momentum states that can be exploited for interferometry and measurements of g. In this talk, I will describe these experimental techniques and their application to coherently prepare helium Rydberg atoms in spatially separated momentum states. I will show how this approach can be adapted to measure g for Rydberg helium atoms, and ultimately employed in tests of the WEP with long-lived Rydberg positronium [4].

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98

CSF welcome address:

Poster Session 2 / 99

Towards quantum control and spectroscopy of single hydrogen molecular ions

Author: Nick Schwegler[1]

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The complexity and variety of molecules offer promising applications in metrology and quantum information that go beyond what is possible with atomic systems. We aim to study light molecular ions that are amongst the most fundamental and simplest molecules. Their internal structure can be calculated, making them prime candidates for the determination of fundamental constants as well as for theory benchmarks.
Spectroscopy of single ions is expected to reduce systematic uncertainties and improve signal strength. However, this requires quantum control over the spectroscopy ion, which can be achieved by co-trapping it with a well-controlled logic ion. Using the technique of quantum logic spectroscopy, it has been shown that even hard-to-control ion species can be prepared in a pure quantum state and measured non-destructively with high precision.
I will present our progress towards full quantum control of the hydrogen molecular ion H_2^+ and its reaction product H_3^+, each co-trapped with a beryllium ion in a linear Paul trap. We have demonstrated H_2^+ trapping times of up to 11^{+6}_{-3} hours, enabled by cryogenic pumping of background H_2 that suppresses chemical reactions converting H_2^+ to H_3^+. We have achieved ground-state cooling of one of the motional modes of both H_2^+ and H_3^+, which is one of the first steps in many implementations of quantum logic spectroscopy. In addition, our cryogenic apparatus should allow for the use of buffer gas to cool the rovibration of molecular ions to their ground state.

Atoms and Exotic Atoms I / 100

Session's intro

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Electric Dipole Moments (EDMs) / 101

Session's intro

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Interferometry / 102

Session's intro

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Molecules / 103

Session's intro

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Quantum Sensors / 104

Session's intro

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Quantum Sensors II / 105

Session's intro

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Ions / 106

Session's intro

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Atoms and Exotic Atoms II / 107

Session's intro

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Poster Session 1 / 108

Two Photon Direct Frequency Comb Spectroscopy of the 1S-3S Transition in Hydrogen

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The energy levels of hydrogen-like systems can be both calculated and measured very precisely. Precision spectroscopy of two transitions at the current level of accuracy allows the determination of the Rydberg constant and the proton charge radius. Comparison with an additional transitions can serve as a consistency check for the theory of quantum electrodynamics. The recent discrepancy in these consistency checks is known as the proton size puzzle.
I will present the latest measurement of the 1S-3S transition in hydrogen, using two photon direct frequency comb spectroscopy and explain the experimental technique along with our setup. The obtained result (f1S-3S = 2,922,743,278,665.79(72) kHz) supports the value of the proton charge radius first obtained from muonic hydrogen. The difference of 2.1 standard deviations of this result and the last measurement of the same transition suggests that the proton size puzzle can be resolved by further investigating the experimental uncertainties. We will give an outlook on the next anticipated measurements, current problems and recent improvements of the experiment.

Poster Session 2 / 109

Towards High-Resolution X-Ray Spectroscopy of Muonic Lithium using Metallic Magnetic Microcalorimeters

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Precision measurements of nuclear charge radii provide important inputs for modern nuclear theory, helping to improve our understanding of nuclear forces. The spectroscopy of muonic atoms is known as a highly precise method for such measurements. However, in the case of low- to medium-Z nuclei, the covered energy range has so far been difficult to access using laser spectroscopy or conventional solid-state detectors. The new QUARTET collaboration addresses this gap for the first time using metallic magnetic microcalorimeters, combining high quantum efficiencies, broadband-spectra and record-resolving power. This contribution presents plans and status of a first experiment aiming at the spectroscopy of muonic Li-6 and Li-6 at the Paul Scherrer Institute.

Poster Session 1 / 110

Hyperfine splitting in muonic hydrogen

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Low-energy properties of the nuclei can be precisely examined via highly accurate measurements of atomic transitions. As the Bohr radius of hydrogen-like atoms decreases with increasing orbiting particle mass, the muonic atoms (hydrogen-like atoms formed by a negative muon and a nucleus) have enhanced sensitivity to nuclear structure effects. The HyperMu experiment is motivated to measure this transition with 1 ppm accuracy in order to deduce the so called two-photon-exchange (sum of Zemach radius and polarizability contributions) contribution with a relative accuracy of 1x10-4. This experiment which is at the crossover between particle, atomic and nuclear physics requires the development of cutting-edge laser technologies especially in the thin-disk laser and the mid-infrared laser domains. The mid infrared source needed for this experiment is realised starting from a single-frequency thin-disk laser operating in the 300 mJ regime and down-converting its pulses in a cascade of nonlinear processes to produce single-frequency pulses of 5 mJ energy at 6800 nm within 1 microsecond after laser trigger. Here, the status and prospects of HyperMu experiment are presented with focus on the recent developments of the midinfrared laser system at PSI.

Poster Session 1 / 113

Progress in laser cooling of Tm atoms

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Cold atoms have many applications in quantum sensors and quantum simulations. Most studies in this field are performed in the so-called cycle mode, where stages of experiment are performed sequentially. Due to the rapid progress in laser systems, funda- mentally different schemes with spatial separation and simultaneous execution of exper- imental stages are now being developed. This approach opens up new areas of research such as optical clocks with continuous interrogation of the clock transition, experiments with matter waves and atomic lasers. In this work we discuss the prospects of a continu- ous source of cold thulium atoms based on a two-dimensional magneto-optical trap that was developed in our laboratory.

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Poster Session 1 / 114

Towards transportable thulium optical lattice clock

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Optical clocks are one of the most precise instruments today with applications ranging from tests of fundamental physics to relativistic geodesy. The 1.14 μm clock transition in neutral thulium has exceptionally low sensitivity to the environment, including electric and magnetic fields and black-body radiation. Together with practical wavelengths of used lasers it makes thulium a perspective candidate for transportable optical lattice clock. We discuss our recent results in thulium optical clock: the concept of synthetic clock frequency, a newly developed compact setup and prospect of building an optical clock with continuous interrogating of a moving cold atoms.

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