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Book of Abstracts

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Welcome

Session 9 / **2**

Towards improved charge radii from Lithium to Neon

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Absolute nuclear charge radii provide essential input to improve our understanding of the strong interaction at low energies, and allow the confrontation of experiment and theory in simple atomic systems. However, precision measurements of the radii of light nuclei above helium have been mostly out of reach of the currently employed methods.

QUARTET is a new experiment aiming to address this gap by performing precision cascade x-ray spectroscopy from μ^6Li to μ^{22}Ne atoms with metallic magnetic calorimeters - a quantum sensing technology capable of high efficiency over a wide energy range with excellent resolution for low-energy x rays. In this talk I will review the physics motivation, describe the experimental scheme, and show preliminary results from a successful test beam.

References:
arXiv:2210.16929
arXiv:2310.03846
arXiv:2311.12014

Poster Session 1 / **3**

Calculations of the even parity P and D states of the carbon atom.

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Variational, nonrelativistic energies of eight states of the carbon atom have been calculated with high precision. The states of interest include two low-lying singlet P and D states, as well as triplet P and D states, all of even parity. The wave functions are expanded in the basis of products of Explicitly Correlated Gaussians and bipolar harmonics.

Poster Session 1 / **4**

Calculation of spin-dependent relativistic corrections in small atoms with one and two p-electrons using explicitly correlated Gaussians

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In the framework of the perturbation theory we consider the fine structure of the energy levels of few-electron atoms and ions in the states with the dominant configuration containing one or two p-electrons (or one d-electron). Using highly accurate expansions
of the nonrelativistic wave functions in terms of all-particle explicitly correlated Gaussians, we derived analytical expressions for matrix elements and then evaluate
the expectation values of the spin-orbit and electron spin-spin interactions. We apply our approach to study the fine structure splittings in the ground ^3P state of the carbon atom. The calculated fine structure includes the leading-order spin-orbit and electron spin-spin corrections ($\propto m\alpha^4$), contribution from the electron anomalous magnetic moment ($\propto m\alpha^5$), and accounts for the coupling between the ground and low-lying excited states (off-diagonal matrix elements between $^3P_0$ and $^1S_0$ states, and between $^3P_2$ and $^1D_2$ states). The calculated values are compared with the available experimental data and NIST Atomic Spectra Database.

Session 2 / **5**

Low energy hydrogen anions source for matter/antimatter precision experiments

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Cold-charged particles play an essential role in interstellar molecular formation, are present in many high-precision experiments, antimatter physics, and chemistry, and are also relevant for studies on the origin of biological homochirality. In this contribution, I will describe a system based on the Matrix Isolation Sublimation (MISu) technique [1],[2] to generate and trap these species in the laboratory. After growing a thin film of Neon upon a cold (4 K) sapphire subtract, we implant different species inside this film via laser ablation of a solid target. With a heat pulse to the sapphire surface, we sublimate the solid neon at low temperatures, and the inert gas carries the particles that were confined inside the solid, producing a beam at low energies. We guide the charged particles using the magnetic field produced by two perpendicular coils and trap the particles in a Penning-Malmberg trap using low voltages (˜1 V) and weak magnetic fields (˜0.1 T).
We have measured energy distribution for positive and negative trapped charge particles whose peak was below 25 meV. Using an on-trap-time-of-flight scheme, we demonstrate the presence of electrons, hydrogen anions, protons, lithium cations and anions, and light molecular ions.
The hydrogen anions can be used to produce a cold sample of neutral trappable hydrogen by near-threshold photodetachment (0.754 eV). For example, a laser at 1575 nm will leave 0.2 K of recoil energy, less than the ion sample's typical temperature or energy dispersion, to the neutral H. The fraction of resulting atoms with energy below 0.5 K can remain trapped in a 1 T trap depth superposed magnetic trap and could be detected using the sensitive technique [3]. These cold H can loaded into the ALPHA [4] antihydrogen trap at CERN toward direct spectroscopic comparison of both conjugated species beyond 13 significant figures. The production is scalable and adaptable to different species, including deuterium and tritium, which is relevant for neutrino mass and fusion research.

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Poster Session 1 / 6

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 energies, nearly at rest. This work is a part of an international collaboration GRASIAN (Gravity, Spectroscopy and Interferometry with Atoms and Neutrons) [1]. The motivation for the work proposed here is associated with weak short-range forces exerted by yet undiscovered light bosons, direct checking of the equivalence principle, CP violation and comparison of the properties of matter and antimatter. We will probe the ultra-low energy domain with hydrogen, the lightest and simplest of neutral atoms, which has served as a test probe of the fundaments of physics throughout the era of modern physics. However, the thermal motion of atoms has set limits to the accuracy of experiments. Therefore, using hydrogen atoms nearly at rest one expects to obtain unprecedented levels of precision.

We have demonstrated magnetic capture and confinement of 10^{15} H atoms at temperature below 50mK using a world largest Ioffe-Pritchard type trap (IPT) recently built in our laboratory [2]. The loading of H into the sample cell (SC) was performed at a fixed temperature of the SC using a temperature controller. The flow of 10^{13}atoms/s was observed by detecting the recombination heat of

H on the SC wall. H flux into SC detected by bolometers and SC thermocontroller. Bolometer is a graphite film resistor painted to Kapton foil 50(or 30) μm with gold electrodes.

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. Atom-fountain experiments with optical Ramsey spectroscopy will improve the accuracy of the 1S-2S interval. Bose-Einstein condensation (BEC) of H bound in the GQS will be attained and used for matter-wave interferometry. Our methods and results will be useful for experiments with antihydrogen pursued at CERN.

Experiments with gravitational states of ultracold neutrons opened a new way for studies of fundamental properties of matter and gravity [3], and similar experiments are suggested for atomic hydrogen and antihydrogen [4, 5]. Recent developments in production and cooling of antihydrogen in CERN demonstrate that such experiments are realistic in the nearest future. Although, there is no reason to expect that gravitational properties of antimatter differ substantially from that of the matter, observation of even a small difference would have a strong impact on our fundamental understanding of nature.

Reaching a natural linewidth (NLW) of $\sim$1.3 Hz for the 1S-2S transition is an ambitious goal for ultrahigh-resolution spectroscopy. Progress in the laser technology allows nowadays reaching the laser linewidth close to 1 Hz [6, 7]. Using such a state-of-the-art light source for studies of ultra-slow atoms, we will push the 1S-2S H spectroscopy to the NLW level. The total estimated uncertainty due to systematic effects was estimated to be at the level of 0.02 Hz for atoms at 1 mK. Since we are planning to work at much lower temperatures with large numbers of atoms, this level seems plausible to be reached. The absolute accuracy will be limited by the precision of the frequency standard available for the project. For our location in Turku the best solution is to use a GPS clock and an active local reference (Cs or hydrogen maser) using a frequency comb for laser locking. Accuracy of approaching 10^{-15} can be reached using such a system.
\This work was supported by the Academy of Finland (grant No. 317141), and Jenny and Antti Wihuri Foundation.*

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Poster Session 1 / **7**

High-precision study of atomic and hyperfine-induced electric dipole polarizability of 133Cs

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The 133Cs atomic clock stands out as the primary standard for timekeeping and frequency regulation. It operates by measuring the microwave transition frequency between the hyperfine levels F = 3 and F = 4 of the 133Cs ground state. However, the precision of this clock is hindered by systematic errors, necessitating accurate determination of the electric dipole (E1) polarizabilities (αd) to account for Stark effects on the clock states. Beyond timekeeping, the transition between the F = 3 and F = 4 hyperfine levels in 133Cs holds promise as qubits in quantum computing. Ensuring reliable

quantum control demands minimizing decoherence in single trapped atoms, emphasizing the need for precise understanding of the clock transition's characteristics. Recently, attention has turned to the differential shift in the clock transition caused by background blackbody radiation, prompting efforts to accurately estimate αd value.

We have precisely determined polarizabilities for the hyperfine levels of the 133Cs ground state. Through meticulous analysis, we provide insights into both static and dynamic electric dipole polarizabilities for the clock transition. The scalar, vector, and tensor components of αd are estimated by expressing as sum of valence, core, core-core, core-valence, and valence-core contributions that are arising from the virtual and core intermediate states. Our calculations demonstrate strong alignment with experimental data for static scalar and tensor components, affirming the reliability of our dynamic polarizability estimates. This reliability is crucial for assessing Stark shifts during high-precision measurements, particularly in the context of utilizing 133Cs clock states.

Source/Reference of the Work: https://doi.org/10.1103/PhysRevA.108.042818

Session 2 / **8**

Metrology of Rydberg-Stark states in the hydrogen atom

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The long lifetimes of highly excited Rydberg states make them very attractive for precision experiments. Until now, these states were disregarded in precision spectroscopic studies of the hydrogen atom, mainly because of their large dc-polarizabilities at nominal zero electric field strength, which result in uncontrollable systematic frequency shifts. Recently, we demonstrated how to circumvent the unwanted influence of the dc-Stark effect in high Rydberg states (principal quantum number $n \geq$20) by measuring individual Rydberg-Stark states ($k = 0, \pm 2$) and using the line positions to correct for the perturbation induced by the electric fields [1].
This approach will be illustrated by measurements of the $n = 24 \leftarrow 2\,^2\mathrm{S}_{1/2}(f = 1)$ and $n = 20 \leftarrow 2\,^2\mathrm{S}_{1/2}(f = 0, 1)$ transition frequencies [2]. The results are used to determine the ionization energy of H with unprecedented accuracy. In combination with the Lamb-shift measurement from Bezginov *et al.* [3] we derive a value of the Rydberg constant that is independent of the exact value of the proton charge radius [2].
This work is supported by the Swiss National Science Foundation through the Sinergia-Program (Grant No. CRSII5-183579) and Grant No. 200020B-200478.

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Session 5 / **9**

Antihydrogen laser spectroscopy to 13 significant figures and beyond

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We describe work at the ALPHA collaboration at CERN that is leading to a 13 significant figures measurement of the 1S-2S transition in antihydrogen with a physics-driven lineshape theory. A future comparison of matter and antimatter in this system at 15 figures or more will be discussed in conjunction with techniques being developed at UFRJ to load hydrogen into the same antihydrogen trap.

Session 3 / **10**

Finite nuclear mass correction to the hyperfine splitting in hydrogenic systems

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A general quantum electrodynamic method is presented, that allows to derive nuclear recoil corrections in hydrogenic systems, which are exact in the nuclear charge parameter $Z\,\alpha$. The exemplary derivation is demonstrated for the $O(m/M)$ nonradiative nuclear recoil correction to the hyperfine splitting.

Session 9 / **11**

Proton Structure in and out of muonic hydrogen

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In this talk, I would like to discuss the theory of light muonic atoms in view of upcoming experiments, e.g., the measurement of the muonic-hydrogen ground-state hyperfine splitting with ppm accuracy. A particular focus will be on predictions of the two-photon-exchange corrections in muonic hydrogen. The leading-order baryon chiral perturbation theory predictions of the proton polarizability contribution will be compared to recent data-driven dispersive analysis.

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Session 4 / **13**

Precision measurements on the (2-0) quadrupole transitions in H₂

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The hydrogen molecule and its isotopologues has become a favorable test bench in the advancement of quantum mechanics in the molecular domain. Comparison between experiment and theory signifies a test of quantum electrodynamics in bound systems and it may be used to probe physics beyond the Standard Model (1). After the focus had been on measurement of the dissociation and ionization energies now it is shifting toward measurement of the rovibrational splittings. The long lifetime of the many (> 300) rovibrational levels in each isotopologue makes them into a benchmark testing system, in fact better than atomic hydrogen which has only one long-lived excited state. For a time it had not been possible to measure rovibrational transitions in saturation, but now that has been achieved, for the heteronuclear species HD (2,3) and HT (4).
Here we report on the next step: precision measurements of the (2-0) overtone rovibrational transitions in the H2 homonuclear species, that can only be probed via a quadrupole transition. The S(0) transition in para-H2 was measured as a narrow Lamb dip yielding an accuracy of 10 kHz. A novel problem was encountered: why only one recoil component observed when two are expected [6]? In the Q(1) line for the first time the hyperfine structure in a vibrational transition in H2 was resolved [7].

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Poster Session 2 / **14**

Positron binding to neutral beryllium atom: relativistic effects and fine structure

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Bound states of positrons with small neutral atoms have not yet been detected experimentally. However, they are expected to have very small positron affinities. Not only does this pose a challenge for modeling such states reliably, but it also raises a question of how important the relativistic effects are and whether they can alter the dynamical stability of the weakly bound positron-atom complexes.In the framework of the variational method we have carried out new improved calculations of three bound states of positronic beryllium. Using large expansions in terms of explicitly correlated Gaussians we generated accurate nonrelativistic wave functions and determined some structural properties and annihilation rates. Next, we investigated the leading-order relativistic effects in all three bound states of positronic beryllium. Our conclusion is that neither the inclusion of scalar relativistic nor spin-dependent corrections alter the predictions regarding the existence of the bound states. When leading-order relativistic effects are taken into account, positron affinities change by about 2% or less. This is so even for the triplet P state of positronic beryllium, where the spin–orbit correction is not at all canceled out when the energy difference with the parent system is computed.

Poster Session 1 / **15**

New Physics contributions to atomic spectra

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Atomic spectroscopy experiments at the precision frontier allow us to study low-energy nuclear structure, test bound-state QED, refine fundamental constants, and potentially find New Physics.

As experimental precision is continuously improved, it is a timely task to re-examine the sensitivity of specific bound states to New Physics scenarios. Depending on their Bohr radii, hydrogen-like systems can be particularly sensitive to distinct New Physics mass ranges.

In this talk, we use the example of axion-like particles to illustrate how spectroscopy experiments can be used to probe New Physics.

Session 1 / **16**

Precise Zeeman structure measurements of light ions at µTEx

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At our Penning-trap experiment µTEx in Heidelberg, Germany, we measure the ground-state hyperfine- and fine-structure splitting of light, hydrogenlike ions in a magnetic field of 5.7T [1]. From these high-precision measurements, the bound-electron and shielded nuclear *g*-factors as well as the hyperfine-structure constant are extracted [2]. In combination with theory, this allows to test QED, to infer the Zemach radius of a nucleus and to precisely determine fundamental constants such as the electron mass. Additional lithiumlike measurements allow testing of nuclear magnetic shielding theory. The results of the latest beryllium-9 campaign [3] and the current status of the helium-4 measurement will be presented.

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Session 3 / **17**

Precision spectroscopy of Rydberg states in ^{4}He and ^{3}He

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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].
Recently, we developed 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. In this talk, we present the the first results on the ionization energy of metastable helium obtained with improved experimental setup and methods, which include (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 np Rydberg states, (iii) the implementation of a new sub-Doppler, background-free detection method, and (iv) the integration of an interferometer-based retro-reflector canceling the 1^{st}-order Doppler shift to enable Doppler-free spectroscopy. We illustrate its power with a new determination of the ionization energy of $2\,^3S_1$ metastable He with a fractional uncertainty in the 10^{-12} range using extrapolation of the np series.
The first results of similar experiments carried out on the ^{3}He isotope are also presented as part of an effort to determine the difference between the charge radii of the $^3He^{+2}$ and $^4He^{+2}$ nuclei.
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Session 6 / **18**

Spin-Rovibrational Structure of the Molecular Hydrogen Ion from Spectroscopy of Rydberg States

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Precision measurements of rovibrational energies in H_2^+ provide access to fundamental constants such as the proton-to-electron mass ratio or the proton charge radius, by comparison with theoretical results [1]. Because H_2^+ and D_2^+ are nonpolar, pure rotational and vibrational transitions are forbidden in the electric-dipole approximation and are very difficult to measure. As alternative method to determine the energy-level structure, spectra of Rydberg series of H_2 and D_2 converging on different spin-rovibrational states of H_2^+ and D_2^+ can be measured, from which their relative energies are obtained by Rydberg-series extrapolation [2, 3].

As application of this method, we determined the fundamental vibrational interval of H_2^+ by continuous-wave laser spectroscopy of Stark manifolds of Rydberg states of H_2 with the ion core in the ground and first vibrationally excited states [4]. From measurements of Stark manifolds at varying electric field strengths and comparison with precise calculations of the field-induced Stark shifts [5], the zero-quantum-defect positions $-R_{H_2}/n^2$ are determined, which yield precise ionization thresholds. We demonstrate the use of this procedure for the determination of the fundamental vibrational interval of H_2^+ at sub-MHz uncertainty.

This contribution also focuses on the determination of the first three rotational intervals of para-H_2^+ ($N^+ = 2, 4, 6$) and their spin-rotation splittings at sub-MHz accuracy by a combination of precision spectroscopy and multichannel-quantum-defect theory.

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Session 1 / **19**

Precision mass ratio measurements of light ions at Florida State University

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After a brief review of atomic mass measurements on light ions with the Florida State University Precision Penning trap, we will present our progress on measurements involving ^{4}He. This is motivated by future measurements of the electron mass via the g-factor of $^4He^+$, and the discrepancy between the two most precise literature values for the atomic mass of ^{4}He.

Session 9 / **20**

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 12 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 methods.

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Poster Session 2 / **21**

Status of the Hydrogen 1S-3S Direct Frequency Comb Spectroscopy Experiment

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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 additional transitions can serve as a consistency check for the theory of quantum electrodynamics. Improvements in these measurements in the last years, revealed small discrepancies, which are not yet fully resolved.
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 value differs by 2.1 standard deviations from the recent measurement of the same transition obtained at Laboratoire Kastler Brossel suggesting, that the discrepancies in these precision measurements probably arise due to yet unknown experimental issues. Therefore, we hope that further investigation of the experiments will resolve this deviation. I will give an update on the status of the experiment, the next intermediate results and the anticipated improvements for the next measurement campaign.

Poster Session 1 / **22**

New apparatus for single-photon Doppler-free VUV/XUV spectroscopy

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The ionisation energies of many atoms and molecules lie in the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) parts of the electromagnetic spectrum, which correspond to wavelengths (frequencies) of light of $< 200\,\mathrm{nm}$ ($> 1.5 \times 10^{15}$ Hz) and $< 105\,\mathrm{nm}$ ($> 2.9 \times 10^{15}$ Hz), respectively [1]. Laser radiation generated at these wavelengths can therefore be utilised to perform single photon excitation from the ground electronic state of an atom or molecule to highly excited electronic states, including direct excitation to Rydberg states with a large value of the principal quantum number, n [1]. However, although VUV/XUV laser sources with $< 250\,\mathrm{MHz}$ bandwidths have been achieved [2-6], large Doppler broadening of transitions at VUV/XUV wavelengths (with Doppler widths typically $> 100\,\mathrm{MHz}$) often limit the achievable resolution of single-photon VUV/XUV spectroscopy. Additionally, large Doppler shifts can result in $> 100\,\mathrm{MHz}$ systematic shifts to measured transition frequencies in the VUV/XUV. We present the development of a new experimental apparatus for performing Doppler-free spectroscopy at VUV/XUV frequencies. This method is based on combining an imaging-assisted single-photon Doppler-free spectroscopy technique, recently developed for precision spectroscopy of Rydberg states of He atoms [7], with a long-pulse-length ($\sim$ 100 ns - 1.0 μs) narrow-bandwidth VUV/XUV laser. The initial aim of such an experiment

is to generate laser radiation with a wavelength of $\sim 80\ \mathrm{nm}$, for use in performing precision single-photon XUV spectroscopy of H_2 molecules excited to high-n ($n > 30$) Rydberg states from the ground $X\,^1\Sigma_g^+$ state.

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Poster Session 1 / **23**

Injection of State-Selectively Prepared Molecular Ions into a Radiofrequency Trap

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Rigorous tests of QED and precise measurements of the proton-to-electron mass ratio are compelling applications for high precision spectroscopy of the dihydrogen cation. We propose to carry out millimeter-wave spectroscopy in the Lamb-Dicke regime on H_2^+ in a radiofrequency ion trap. This technique enables Doppler-free spectroscopy with a high signal-to-noise ratio, when used in conjunction with injection of state-selectively prepared ions. Ions originate in mass-analyzed threshold ionization in a supersonic beam of neutral hydrogen excited to a Rydberg state with the desired rovibrational configuration. Ions produced by direct photoionization that exist prior to the field ionization are rejected using a prepulse. The cloud of ions is extracted from the neutral beam using an electrostatic quadrupole deflector, before being injected axially into a linear radiofrequency trap and being decelerated by a static potential. Transitions are detected by driving transitions to the dissociated continuum states, producing protons as photodissociation products. The radiofrequency trap is operated in a regime where the protons remain stable radially, but have sufficient kinetic energy to overcome the axial confinement in a selected direction, ensuring near-unity detection efficiency. To this end, we have developed detailed simulations of our ion beam and an experimental apparatus for testing these novel techniques.

Session 3 / **24**

Bound state energy levels from trace anomaly

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Results on calculations of bound state energy levels from trace anomaly will be presented.

Session 3 / **25**

Hyperfine structure calculations in hydrogenlike and heliumlike atoms

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We will present the current status of QED theory for hyperfine structure in hydrogenlike and heliumlike atoms in comparison to precision experimental results. For ^{3}He$^+$ we use this comparison to obtain the nuclear polarizability effect. In the case of ^{3}He atom we derive theoretical result for 2^3S hyperfine splitting with uncertainty of 41 Hz and observe excellent agreement with the experimental data. For ^{6,7}Li$^+$ we use the comparison between theory and experiment to obtain the effective Zemach radius. We confirm the surprising result that the effective Zemach radius of ^{6}Li is smaller than that of ^{7}Li. Lastly, we use the results for the nuclear structure obtained from Li$^+$ to obtain accurate theoretical predictions for the hfs in ^{6,7}Li^{2+} for which no experimental data is available so far.

Session 5 / **26**

Production of a 6 keV antihydrogen beam in the GBAR experiment

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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 μK 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 the production of $6\,\mathrm{keV}$ $\overline{\mathrm{H}}$, a milestone for the experiment, as well as the status and future prospects of GBAR [GBAR, EPJC 83, 1004 (2023)].

Session 3 / **27**

Precision Measurement of Vibrational Quanta in Tritium Hydride

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The spectroscopic investigation of the hydrogen molecule and its isotopologues is playing a crucial role in the advancement of quantum mechanics in the molecular domain. Particularly, highly accurate measurements of rovibrational transitions allow for various tests of fundamental physics including searches for physics beyond the Standard Model.
To carry these investigations on the tritium-bearing isotopologue HT, we developed a NICE-OHMS (noise-immune cavity-enhanced optical-heterodyne molecular spectroscopy) setup complying with technological challenges regarding confinement and chemistry of the radioactive tritium.
From this setup we present Doppler-free measurements on the (2,0) overtone band of the tritium hydride molecule.

Poster Session 1 / **28**

High Precision Spectroscopy of the Hydrogen Molecule and its Ion

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This project aims to perform spectroscopy of H_2 above the n=2 and n=3 dissociation limits to observe its photofragments utilizing velocity map imaging (VMI) and study the competition between predissociation and autoionization by measuring the energy and angular distribution of the Hˆ+ and H_2ˆ+ ions [1]. To this end, the molecule is first excited via a one-photon transition to the B state using a tunable XUV laser, and simultaneously a second photon is used to induce a transition above one of these dissociation limits, which causes the molecule to fragment.

Using a suitable intermediate state and a third photon, molecular Rydberg states can be excited with the ion being in various excited rovibrational levels. Employing pulsed field ionization, this establishes a new approach to selectively generate molecular ions in a single quantum state [2]. This is especially important for homonuclear molecules where the vanishing dipole moment prohibits the use of unselective ion production via electron impact. Precision measurements based on weakly bounds states of the molecular hydrogen ion exhibit high sensitivity to peculiar effects predicted by quantum electrodynamics theory and even to possible manifestations of physics beyond the Standard Model [3].

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Poster Session 1 / **29**

Low Repetition Rate Optical Frequency Combs for Precision Spectroscopy

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The extreme ultraviolet (XUV) frequency comb is an indispensable tool for extending optical frequency metrology into the unexplored wavelength range below 200 nm. With XUV frequency combs, precision spectroscopy for fundamental physics, optical clocks and laser cooling can be extended into the XUV regime for the first time. This includes applications in the spectroscopy of hydrogen-like ions such as highly charged ions, nuclear excitations of Th^{+}, and our planned experiment on the spectroscopy of the He^{+} 1S-2S transition for testing quantum electrodynamics [1,2].

Historically, the generation of XUV lasers has been a daunting task, requiring either particle accelerators or high harmonic generation (HHG) techniques with peak intensities on the order of $10^{13} - 10^{15}$ W/cm^2. Our current approach involves boosting the average power of an infrared frequency comb to 8 kW before HHG converts it into an XUV frequency comb. While effective, this method introduces complexity and requires special measures to protect optical components from the rigors of high-power lasers.

To overcome this challenge, this work explores a novel path: the use of low repetition rate optical frequency combs for frequency conversion [3]. By reducing the repetition rate while increasing the peak power, we could perform HHG at a lower average power, effectively simplifying the laser system. The technique relies on pulse picking using an acousto-optic modulator (AOM) that selects pulses at specific intervals, effectively reducing the repetition rate. The carrier-envelope offset (CEO) frequency can be preserved after pulse picking, as long as certain synchronicity requirements are met [3].

This research focuses on the pulse-picking of an infrared frequency comb generated by a Kerr-lens mode-locked Yb:KYW oscillator with a repetition rate of 40 MHz. Pulse-picking with an AOM, which reduces the repetition rate to 40 kHz, and subsequent amplification with multiple stages of diode-pumped double-pass Yb:LuAG amplifiers allows the pulse energy to be increased to 4.2 μJ, with future plans to further increase the pulse energy to 50 - 100 μJ. Notably, the pulse characteristics of this frequency comb, including 1.3 ps pulse duration and 1.5 nm spectral width (measured by frequency-resolved optical gating), remain consistent with our cavity-enhanced HHG system developed at 40 MHz repetition rate and 8 kW circulating power [1]. The main difference is the significantly reduced repetition rate, which results in a three order of magnitude reduction in average power. The results demonstrate the feasibility of generating XUV frequency combs using HHG with infrared average powers as low as 10 W. The primary limitation is the transition linewidth of the spectroscopic target, which cannot exceed 20 kHz. However, this can be overcome by using two low repetition rate frequency combs and performing XUV dual comb spectroscopy on the target.

This innovative approach offers a tantalizing prospect: XUV frequency combs that do not require high average powers or particle accelerators. It opens new horizons for XUV frequency comb spectroscopy, making it more accessible to researchers across disciplines. The allure of exploring the XUV spectrum without significant barriers is likely to capture the interest of scientists and researchers, fostering exciting opportunities for scientific exploration.

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Session 5 / **30**

Measuring the neutron electric charge with time-of-flight grating interferometry

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Neutron grating interferometers can be employed as powerful tools to perform high-precision measurements of deflection angles and scattering. A novel concept of a symmetric Talbot-Lau interferometer using three identical absorption gratings in a time-of-flight mode is under development at the University of Bern. The ultimate goal of this project is to conduct a sensitive measurement of the neutron electric charge and to improve the current best upper limit : Qn < (-0.4+/-1.1) * 10^-21 e [Baumann, 1988]. A proof-of-principle apparatus has been characterized at the cold neutron beamline PF1b at the Institute Laue-Langevin in Grenoble, France. A description of the experiment, alignment procedures and first results concerning beam deflections measurements, the setup stability and the neutron electric charge will be presented

Session 3 / **31**

Precision spectroscopy of helium atoms

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Precision spectroscopy in few-body atomic systems, like hydrogen and helium, enables the testing of the quantum electro-dynamics (QED) theory and determination of the fundamental physical constants, such as the Rydberg constant, the proton charge radius, and the fine-structure constant. It also sets constraints on new physics beyond the standard Model (BSM). High precision spectroscopy of atomic helium, combined with ongoing theoretical calculations for the point nucleus may allow an alternative determination of the helium nuclear charge radius, which could be more accurate than from the electron scattering. Moreover, the comparison of results from electronic and muonic helium will provide a sensitive test of universality in the electromagnetic interactions of leptons.
Our group has performed laser spectroscopy measurement of the 23S-23P transition of helium atoms, in the past decade [1,2]. Recently, we updated our atomic beam setup, adding a Zeeman deceleration system, we implemented a new metastable atomic helium beam with high brightness and adjustable speed [3]. In this setup, the influence of first-order Doppler effect can be significantly reduced. At the same time, we have improved the probe laser system, by using a switching traveling wave field instead of the standing wave field that used in the original experiment, to probe the atomic beam [4]. This improvement effectively reduces the light force induce shift in our previous measurement [5]. Based on that setup, the issue of post-selection in precision spectroscopy of the 23S–23P transition of 4He has first revealed. We experimentally observed a discrepancy between the results with and without post-selection, which is validated by our simulations and theory. Our findings reveal the extra bias of weak signals when applying WVA and indicate a correction of previously experimental results obtained under post-selections. Our work highlights the significance of quantum mechanics and technologies in modern precision measurement and appeals to more attention to evaluate and interpret experiments in the framework of quantum optics and quantum metrology.

Key words: Helium Spectroscopy, Post-Selection, Weak Measurement, Isotope Shift, Nuclear Charge Radius
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Session 7 / **32**

Hyper-EBIT: A source for heavy highly charged ions

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ALPHATRAP is a Penning trap experiment located at the Max-Planck-Institut für Kernphysik, Heidelberg with the goal to perform tests of quantum electrodynamics (QED) in strong fields by measuring the bound electron magnetic moment or g factor [1]. These tests are performed using highly charged ions, where the few remaining electrons experience the strong fields emanating from the nucleus. Recently, the g factor of $^{118}Sn^{49+}$ was measured at ALPHATRAP with sub parts-per-billion precision, one of the most stringent tests of bound-state quantum electrodynamics, up to two-loop contributions, in very strong fields [2]. In order to push such tests even further, into the most extreme field strengths, similar measurements should be performed with the heaviest highly charged ions such as $^{208}Pb^{81+}$, where the electric fields reach up to 10^{16} V/cm.

The production of $^{208}Pb^{81+}$ involves overcoming the ionization energy of 100 keV. To produce and inject $^{208}Pb^{81+}$ into the cryogenic Penning trap of ALPHATRAP, we are currently constructing the "Hyper-EBIT", an electron beam ion trap designed for electron beam energies of 300 keV and currents of about 500 mA. I will be presenting the current status of Hyper-EBIT development.
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Session 7 / **33**

Latest results and status update from the Fermilab Muon g-2 experiment

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In August 2023, the Fermilab Muon g-2 experiment collaboration published the Muon g-2 value with an unprecedented precision of 203 ppb, utilising data gathered from 2018 to 2020 (Runs 1-3). Since then, additional data has been gathered from 2021 to 2023 (Runs 4-6), double the Run 1-3 dataset. This talk will focus on the analysis conducted for the latest results, highlighting the systematic studies and enhancements undertaken to reduce systematic uncertainties, thereby advancing the precision of our measurements. Additionally, a brief update will be provided on the current status of the Run 4-6 analysis.

Session 5 / **34**

The neutron lifetime experiment τSPECT

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The τSPECT experiment, which has been developed at
the pulsed Ultracold Neutron (UCN) source of the TRIGA Mainz research reactor and has been moved to the UCN source
at PSI in 2023, employs a fully magnetic trap for UCN and the novel technique of spin-flip loading to measure the lifetime of the free neutron.
The state of neutron lifetime measurement, τSPECT's design and plans for a sub-second precision measurement in the next years will be presented.

Session 1 / **35**

Laserspectroscopic determination of the nuclear charge radii of ^{12,13}C

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Light heliumlike systems are ideal cases to benchmark state of the art atomic and nuclear theory as their nuclei exhibit interesting cluster and halo structures and their atomic structure is accessible for high-precision *ab initio* calculations. With recent progress in nonrelativistic quantum electrodynamics (NRQED) calculations [1], even an all-optical extraction of absolute nuclear charge radii from light heliumlike systems became possible. In an ongoing effort, we therefore plan to determine absolute and differential nuclear charge radii, R_C and δR_C, of the light elements Be to N by purely using collinear laser spectroscopy (CLS) and *ab initio* NRQED calculations. As a first step, we measured the absolute transition frequencies of the $1s2s\,^3\mathrm{S}_1 \rightarrow 1s2p\,^3\mathrm{P}_J$ lines of $^{12,13}\mathrm{C}^{4+}$ at the ppb precision level using the Collinear Apparatus for Laser Spectroscopy and Applied Science (COALA) at the Technical University of Darmstadt.

We present two prospects of our latest results: The use of the $^3\mathrm{P}_J$ frequency splittings to identify the dominant terms in the next order ($m\alpha^8$) of the power expansion of the NRQED calculations and the determination of R_C^{12} as well as $\delta R_\mathrm{C}^{12,13}$ to benchmark *ab initio* nuclear structure calculations [2]. Particularly, the analysis of $^{13}\mathrm{C}^{4+}$, which is modulated by significant hyperfine-induced mixing, poses an additional challenge. Our nuclear model-independent charge radii are compared to new in-medium similarity renormalization group (IMSRG) and no-core shell model (NCSM) calculations as well as existing results from elastic electron scattering and muonic atom spectroscopy. Future plans and perspectives on how to extend the CLS measurements to heliumlike Be, B and N are outlined.

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Session 7 / **36**

Quantum Electrodynamics and Quantum Cyclotron Energy Levels

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Relativistic and quantum electrodynamic corrections to the energy levels of quantum cyclotron states is are important for the determination of a number of fundamental constants, notably, for the g factor of the electron and positron, and atomic masses. We have recently analyzed the relativistic corrections in detail in [Phys. Rev.A vol. 106, 012816 (2022)] on the basis of higher-order Foldy-Wouthuysen transformations. Small modifications of literature values were found. The evaluation of quantum electrodynamic corrections requires the evaluation of bound-state Feynman diagrams with up to six magnetic vertices [Phys. Rev. D vol. 108, 036004 (2023)] and the use of fully relativistic Landau levels in the symmetric gauge, which were derived in [Phys. Rev. D vol. 108, 016016 (2023)]. Apparatus-dependent effects could limit the ultimate precision of the determination of the electron g factor [Phys. Rev. D vol. 107, 076014 (2023)], with the main apparatus-dependent effects impacting the so-called axial frequency. (As a supplement, a few other recent results such as those from arXiv:2403.07127, will be briefly summarized.) *This research was supported by NSF Grant PHY-2110294.

Poster Session 2 / 37

Weighted average of scattered data: a Bayesian approach

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A common problem for experimental scientists is computing averages of scattered data, i.e., with uncertainties much smaller than the distance between the different values. In such a case, a weighted average generally gives a very small uncertainty that does not reflect the bad agreement of the data. Different strategies are implemented in the literature, such as the application of a scale factor to the weighted average uncertainty proportional to a measure of the data scattering, like in the Particle Data Group (PDG) recommendations. Such methods are, however, based only on scientific intuitions without any strict statistical arguments.

We present here a rigorous and reproducible approach based on Bayesian statistics. The starting point, already known in the literature, is to consider each datum uncertainty σ_0 as a lower boundary estimation of the real unknown uncertainty σ. Once marginalised over σ values (using a Jeffreys prior), the expected statistical distribution is no longer a normal distribution but is characterised by smoothly decreasing wings. Like the derivation of the standard weighted average rule, our modified version is obtained by taking the maximum of the cumulative probability distribution and its second derivative value at the maximum. Unlike the standard weighted average, no analytical solution is available, and numerical methods have to be implemented. After a series of tests, the proposed method proved to be very reliable and robust for scattered data, but also with respect to the possible presence of outliers. In particular, it reproduces well the scale factor values reported by the PDG, but also suggests that the PDG method may be biased. When applied to the CODATA recommended values of the gravitational constant G our method proves a very good estimation of G for each CODATA edition, even for critical data sets (1996 edition) that included misleading measurements and where a scale factor of 37 was introduced in the final average value. The presented method will be extended in the future to correlated measurements, for applications to case such as the proton radius puzzle.

Session 6 / **38**

Cavity-enhanced spectroscopy of H_2 in a deep cryogenic regime

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We introduce, for the first time, a spectrometer based on a high-finesse optical resonator operating in a deep cryogenic regime, i. e., below 5 K. This system enables uniform cooling of the entire optical cavity, including the gas sample, the mirrors as well as the piezoelectric actuator (with tunability range exceeding 20 μm [1]). The setup is designed in a way that efficiently attenuates both external vibrations and those originating from the cryocooler itself, ensuring stable operation of the optical cavity.

The spectrometer, integrated with an optical parametric oscillator (OPO), facilitates the investigation of the fundamental band of H_2 in the range from 2.2 to 2.4 μm. We will demonstrate our first measurements of the rovibrational transition S(0) from 1-0 band in cold molecular hydrogen at 5 K in the Doppler-limited regime. Achieving accuracy at the level of 10^{-6} cm^{-1}, our system allows for testing of the quantum electrodynamics (QED) corrections for H_2 at the fifth significant digit of the QED correction [2-3]. By saturating the very weak quadrupole transitions in H_2 we expect to further enhance the accuracy by an order of magnitude. This is achievable thanks to the deep cryogenic regime of our cavity and high laser power provided by the OPO.

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Session 7 / **39**

Testing quantum electrodynamics in extreme fields using helium-like uranium

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Transition energy measurements in heavy, few-electron atoms are a unique tool to test bound-state QED in extremely high Coulomb fields, where perturbative methods cannot be implemented. In such fields, the effects of the quantum vacuum fluctuations on the atomic energies are enhanced by several orders of magnitude with respect to light atoms. However, up to now, experiments have been unable to achieve sensitivity to higher-order (two-loop) QED effects in this strong regime. Here we present a novel multi-reference method based on Doppler-tuned x-ray emission from fast uranium ions stored in the ESR ring of the GSI/FAIR facility. By accurately measuring the relative energies between $2p_{3/2} \rightarrow 2s_{1/2}$ transitions in two-, three-, and four-electron uranium ions, we were able, for the first time in this regime, to disentangle and test separately high-order (two-loop) one-electron and two-electron quantum electrodynamics (QED) effects, and set a new important benchmark for QED in the strong field domain [1]. Moreover, the achieved accuracy of 37 parts per million allows us to discriminate between different theoretical approaches developed throughout the last decades for describing He-like systems.

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Session 5 / **40**

Precision measurements on protons and antiprotons in the BASE collaboration

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Precision measurements of conjugate particles and antiparticles test CPT invariance, a fundamental symmetry in the Standard Model of particle physics. Penning traps can precisely measure the charge-to-mass ratios and magnetic moments of charged particles. The BASE collaboration is performing such measurements on single trapped protons and antiprotons, and reported recently a charge-to-mass ratio comparison of the proton and antiproton with 16 parts per trillion (ppt) relative uncertainty [1]. The magnetic moments of the proton and antiproton were measured with 300 ppt in the BASE-Mainz apparatus [2] and with 1600 ppt in the BASE-CERN experiment [3], respectively. Presently, precise control of magnetic field gradients in the measurement trap and highly optimized resistive cyclotron cooling in a dedicated cooling trap enable improved magnetic moment measurements in the BASE-CERN experiment. Further, we have developed a sympathetic cooling method by image-current coupling between two traps to cool single protons and antiprotons for precision measurements [4], and developments regarding ground-state cooling and quantum logic methods for protons and antiprotons are ongoing in BASE Hannover [5]. As next step, we aim to implement transportable antiproton traps to relocate antiproton precision measurements into laboratories with calm magnetic field conditions to circumvent limitations by magnetic field fluctuations imposed by the operations in the antiproton decelerator hall. We are presently setting up the BASE-STEP trap system in a transportable superconducting magnet to demonstrate the relocation of an antiproton reservoir [6].
I will present an overview of the physics goals, methods, and recent developments in the BASE collaboration.
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Session 6 / **41**

Rovibrational energy levels of the hydrogen molecule and its isotopologues from relativistic nonadiabatic calculations

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The energy of a molecular rovibrational level is theoretically derived from several components, including nonrelativistic, relativistic, quantum electrodynamics, and more. When it comes to a light molecule such as hydrogen or its isotopologue, the nonrelativistic quantum electrodynamics (NRQED) can accurately describe this energy using an expansion in powers of the fine structure constant $E(\alpha) = \sum_{i=2}^{\infty} \alpha^i \, E^{(i)}$.
The component that is least accurate in this expansion is limiting the accuracy of the total energy. Precise predictions for hydrogen molecular levels require the treatment of electrons and nuclei on an equal footing. While nonrelativistic theory has been effectively formulated this way, calculations of relativistic and quantum electrodynamic effects with well-controlled numerical precision are much

more challenging. In this communication, we report extending this nonadiabatic method to the relativistic correction term, $E^{(4)}$. The four-body nonadiabatic James-Coolidge wave function is applied to evaluate the expectation value of the Breit-Pauli Hamiltonian. The main obstacle encountered in this approach is the need for a whole class of integrals resulting from combining relativistic operators with exponential basis functions. Such integrals have been successfully evaluated, and new results of the relativistic correction will be reported. The convergence analysis indicates that the numerical uncertainty of this correction is of the order of 10^{-7} cm^{-1}. Similar to the nonrelativistic component, the uncertainty of the relativistic term is negligible enough to eliminate it from the overall uncertainty budget. An essential aspect of the newly developed method is its capability of handling arbitrarily high rotational angular momentum without significant loss in accuracy. With the new relativistic results, the achieved accuracy is limited only by the uncertainty of the quantum electrodynamic effects, $E^{(n)}$, $n \geq 5$.

Several recent experimental studies have revealed a minor discrepancy between the most precise theoretical and experimental data. This inconsistency offers an opportunity for further advancements in the field. It will be examined in light of new nonadiabatic relativistic calculations, providing insight into further improvements in the current theory.

Session 6 / **42**

Quantum Logic Spectroscopy of the Hydrogen Molecular Ion

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I will present our latest results, implementing pure quantum state preparation, coherent manipulation, and non-destructive state readout of the hydrogen molecular ion H_2^+. The hydrogen molecular ion H_2^+ is the simplest stable molecule, and its structure can be calculated ab-initio to high precision. However, challenging properties such as high reactivity, low mass, and the absence of rovibrational dipole transitions have thus far strongly limited spectroscopic studies of H_2^+. We trap a single H_2^+ molecule together with a single beryllium ion using a cryogenic Paul trap apparatus, achieving trapping lifetimes of $11\mathrm{h}$ and ground-state cooling of the shared axial motion [1]. With this platform we have recently implemented Quantum Logic Spectroscopy of H_2^+. We utilize helium buffer-gas cooling to prepare the lowest rovibrational state of ortho-H_2^+ (rotation $L = 1$, vibration $\nu = 0$). We combine this with quantum-logic operations between the molecule and the beryllium ion for preparation of single hyperfine states and non-destructive readout, and demonstrate Rabi flopping on several hyperfine transitions. Our results pave the way to high-precision spectroscopy studies of H_2^+ which will enable tests of theory, metrology of fundamental constants, and an optical molecular clock.

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Session 8 / **43**

Progress in the calculation of order α^7 radiative-recoil corrections to the energy levels of muonium and positronium

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Muonium and positronium, the $e^-\mu^+$ and e^-e^+ bound systems, are described almost completely within quantum electrodynamics. Their energy levels can be calculated to high precision, and these systems are also subject to high precision measurements. Recent developments include intense experimental work on muonium by the MuSEUM collaboration at J-PARC, the MuMASS collaboration at PSI, and a new measurement of the positronium fine structure by the Cassidy group at UCL. In order to match the uncertainties of projected experimental results the calculation of additional higher order corrections will need to done.

In this talk I will describe progress on a calculation of a set of radiative-recoil corrections to the energy levels of muonium and positronium at order α^7. These are terms involving two-loop radiative corrections to the exchange of two photons betweeen the bound fermions. There are 38 distinct Feynman graphs of this type, leading to a large number of three-loop Feynman integrals. Integration by parts identities were used to reduce the number of independent integrals that need to be done, and their evaluation is being accomplished by solving first order differential equations satisfied by groups of the needed integrals. The variable being used is the ratio x of the two fermion masses. Since results for all values of x are anticipated, the results will be applicable to both muonium and positronium.

Session 9 / **44**

Status of the FAMU experiment

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The FAMU collaboration aims to measure the hyperfine splitting of the muonic hydrogen in the ground state, a way to get insight into the proton magnetic structure.
In 2023, the experiment has successfully acquired data using the complete setup for the first time. Based at the Rutherford Appleton Laboratory (UK), the experiment consists in directing a muon beam onto a gas target to form muonic hydrogen. Then, a mid-infrared pulsed laser, specifically developed by the collaboration, is injected in the target. The laser wavelength is tuned in a window around 6.8 μm to search for the hyperfine splitting resonance.
This contribution will focus on the status of the experiment and the performances during the most recent beam time.

Session 9 / **45**

Nuclear contributions to two-photon exchange in muonic deuterium

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Nuclear structure effects on the energies of light (ordinary and muonic) atoms are the dominant source of uncertainty in the determination of the nuclear charge radii and other properties of light nuclei [1], [2]. The most important of these effects are the two-photon exchange (TPE) contributions. The present method of choice for studying them is ab initio theoretical calculations. In this talk, I

will consider TPE contributions to the energy spectra of muonic deuterium, concentrating on recent results obtained within the framework of pionless effective field theory [3,4].

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Session 4 / **46**

Tabletop particle physics and cosmology with precision quantum-logic spectroscopy

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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 begin with a brief review of optical atomic clocks, focusing on clocks based on quantum-logic spectroscopy of Al^+. I will proceed to present a frequency ratio measurement between Al^+ and Yb clocks at NIST that used a new coherent clock comparison protocol called differential spectroscopy in order to achieve the highest precision of any interspecies ratio measurement to-date. I will conclude with a discussion of two new experiments being set up at UCLA aimed at performing precision quantum-logic spectroscopy of transitions with much higher sensitivity to BSM physics in a variety of sectors. In the first, precision measurements of the 148 nm nuclear isomer transition in sympathetically laser cooled $^{229}Th^{3+}$ ions will be used to search for proposed ultralight scalar dark matter models such as the relaxion and for time-variation of the fundamental constants predicted by theories that seek to unify general relativity with quantum mechanics. In the second, quantum control and quantum-logic spectroscopy of polyatomic molecules will be used to study and search for fundamental symmetry violations in the weak and strong force sectors.

Poster Session 1 / **48**

High precision calculation of structural properties of three-body molecular ions

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The investigation on high-precision calculations of molecular ions emerges as a captivating and fascinating domain of research. The meticulous exploration of molecular ions necessitates a com-

prehensive understanding of their structural, electronic and dynamic properties. In a molecular system, unlike in an atomic system, describing nuclear motion is significantly more complicated due to the constraints on its movement. Consequently, calculations beyond the Born-Oppenheimer approximation become exceedingly intricate. Apart from the approximation method, such as *coupled-cluster*, *density functional*, *perturbation* theory etc., the *Ritz variational* method turns out to be one of the most efficient methods to accurately determine structural properties of a three-body molecular system [1-4]. In this work, we have studied the structural properties of various symmetric and asymmetric molecular three-body systems, such as H_2^+, D_2^+, T_2^+, HD+, DT+ (and their muonic substitutions) *etc.*, using the trial wave function expanded in explicitly correlated *Hyllerass* type basis set of the form: $\Psi\left(r_1, r_2, r_{12}\right) = \left(1 + k\hat{P}_{12}\right) \sum_{i=1}^{N} C_i r_1^{l_i} r_2^{m_i} r_{12}^{n_i}\, exp\left(-\alpha_i r_1 - \beta_i r_2 - \gamma_i r_{12}\right)$, where (r_1, r_2, r_{12}) are the relative coordinates, $\hat{P}_{12}$ is the two-particle permutation operator, (l_i, m_i, n_i) and $(\alpha_i, \beta_i, \gamma_i)$ are basis set parameters and non-linear exponents, $k = +1(-1)$ is for symmetric singlet (triplet) and $k = 0$ is for an asymmetric system. Further, we consider an additional large parameter M in the power of inter-nuclear distance r_{12} to ensure that the factor $r_{12}^{n_i+M} exp\left(-\gamma_i r_{12}\right)$ replicates the notion of Gaussian profile essential for capturing the localized nature of nuclear motion. The *stabilization method* [5] is utilized to accurately determine the energy eigenvalues and geometrical quantities (such as expectation values of inter-nuclear distance, nuclear-particle separation, corresponding angles, cusps *etc.*) of ground and some low-lying singly excited states, as well as continuum embedded *Feshbach* resonance states. Moreover, we have tried to expand the present explicitly correlated method to assess its viability in investigating *four-body* molecular systems, such as Ps_2 and H_2 molecules, which offer intriguing characteristics unique to such systems.

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Session 9 / **51**

Precision Measurements of Muonium and Muonic Helium Hyperfine Structure at J-PARC

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At the J-PARC Muon Science Facility (MUSE), the MuSEUM collaboration is planning new precision measurements of the ground state hyperfine structure (HFS) of both muonium and muonic helium atoms.
Muonium (a bound state of a positive muon and an electron) and muonic helium (a helium atom with one of its electrons replaced by a negative muon) are both hydrogen-like atoms. Their respective ground-state HFS results from the interaction of the electron and the muon magnetic moment, and they are very similar but inverted because of the different signs of their respective muon magnetic moments. High-precision measurements of the muonium ground-state HFS are recognized as the most sensitive tool for testing bound-state quantum electrodynamics (QED) theory to precisely probe the Standard Model [1] and determine fundamental constants of the positive muon magnetic moment and mass. The same technique can also be employed to measure muonic helium HFS and obtain the negative muon magnetic moment and mass. Moreover, muonic helium HFS is also a sensitive tool to test and improve the theory of the three-body atomic system.
The MuSEUM collaboration already performed HFS measurements at zero magnetic field at MUSE D-line of both muonium and muonic helium atom, with results more accurate than previous measurements [2-4]. High-field measurements are now in preparation at the MUSE H-line, using ten

times more muon beam intensity than at the D-line, and with decay positrons/electrons being more focused on the detector due to the high magnetic field, we aim at improving the accuracy of previous measurements by ten times for muonium and hundred times or more for muonic helium. Furthermore, a new experimental approach to recover the negative muon polarization lost during the muon cascade process in helium is being investigated by repolarizing muonic helium atoms using a spin-exchange optical pumping (SEOP) technique [5], which would drastically improve the measurement accuracy, and where a direct improvement by a factor of ten may be realized. An overview of the different features of these new HFS measurements and the latest results will be presented.

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Session 2 / **52**

GRASIAN: Improved measurements with cold hydrogen and deuterium for the forthcoming first demonstration of gravitational quantum states of atoms

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A low energy particle confined by a horizontal reflective surface and gravity settles in gravitationally bound quantum states. These gravitational quantum states (GQS) were so far only observed with neutrons, by Nesvizhevsky and his collaborators at ILL. However, the existence of GQS is predicted also for atoms. The GRASIAN collaboration pursues the first observation of GQS of atoms, using a cryogenic hydrogen beam. This endeavor is motivated by the higher densities, which can be expected from hydrogen compared to neutrons, the easier access, the fact, that GQS were never observed with atoms and the accessibility to other hypothetical short range interactions.
We report on our methods developed to reduce background and to detect low velocity atoms, which are needed for such an experiment. Furthermore, we present our recent measurement results on the collimation of the hydrogen beam to 2 mm, the reduction of background and improvement of signal-to-noise and finally our first detection of atoms with velocities < 72 m s−1.

Session 1 / **53**

Penning Trap Measurement of the ^{3}He Mass

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The masses of lightest nuclei form a network of parameters used in fundamental physics. The mass difference of T and ^{3}He, for example, must be known with the highest precision to cross-check the systematic uncertainties in experiments

such as KATRIN or Project-8, which study β-decay of T to set a limit on the $\overline{\nu}_e$ mass. A Penning-trap measurement involving the bound electron g-factor can improve the precision of the atomic mass of the electron $A_r(e)$ if the mass of the reference nucleus, ^{4}He, is known with sufficient precision.

Penning trap mass measurements of the light nuclei have revealed considerable inconsistencies between the values reported by different experiments. To restore confidence in the literature values, the mass spectrometer LIONTRAP has measured the masses of the proton [1], the deuteron, the HD^+ molecular ion [2], and most recently, ^{4}He [3]. This contribution presents the preliminary results of the ^{3}He mass measurement campaign, aimed at resolving the discrepancy among the literature values known as the ''Light Ion Mass Puzzle".

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Poster Session 2 / **54**

The Mu-MASS Experiment - Status and Outlook

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Muonium is a purely leptonic bound state of an anti-muon and an electron and is an excellent candidate to probe bound state QED and search for new physics beyond the Standard Model. The Mu-MASS experiment at PSI aims to improve the Muonium 1S-2S transition and Lamb Shift by several orders of magnitude. I will present the experiment's progress, focusing on new advances in our understanding of muonium sources as well as the outlook for the experiment.

Poster Session 2 / **55**

Evaluation of self-energy correction in a finite-basis approximation

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The accurate computation of QED corrections to the energy levels of heavy atoms and molecules poses a significant challenge. At the one-loop level the corrections to the electron-nucleus interaction are the vacuum polarization and the electron self-energy. The leading-order (in $Z\alpha$) vacuum polarization correction can be included in molecular computations as an effective local potential (Uehling potential) [1]. However, higher order corrections become increasingly complex. Recently the complete many-potential vacuum polarization density has been evaluated in the finite-basis approximation [2]. Self-energy on the other hand emerges as a non-local interaction, making its rigorous evaluation more involved. The main difficulty in both cases is applying an efficient renormalization scheme to obtain accurate results without loss of precision due to numerical cancellations. Additionally, in order to extend the approach towards more complex systems, it must comply with the well-established framework for many-electron systems. In this contribution we present a method where the solutions of the external-Coulomb-field Dirac equation are expanded in a finite Gaussian basis set, and the partial wave renormalization scheme [3,4,5] is applied to the self-energy problem

of hydrogen-like atoms. The unrenormalized bound self-energy is evaluated for each set of intermediate states with a given κ quantum number separately. The mass renormalization counterterm for each partial wave is treated on equal footing in a finite-basis, avoiding the need for the analytical solutions and complicated multi-dimensional or complex-contour numerical integration. With each term being finite in the partial wave expansion, the UV regulator can be removed to obtain a finite contribution. Our numerical approach shows good agreement with the results of Quiney and Grant, using a numerical complex-contour integral scheme [5].

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Session 2 / **56**

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

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Similar to atomic hydrogen, precision laser spectroscopy of atomic deuterium can be used to determine physical constants and to test Quantum Electrodynamics. A combination of the 1S-2S transition frequency with additional measurements in deuterium allows a determination of the deuteron radius independent of the proton radius (1). These determinations are however discrepant with results obtained in muonic deuterium (2), similar to the proton radius puzzle in hydrogen. Contrary to hydrogen (e.g. (3)), no recent measurements in deuterium are available.

In contrast to hydrogen, precision spectroscopy of the same transition in deuterium is complicated by the simultaneous excitation of unresolved hyperfine components, possibly leading to quantum interference between unresolved lines (4). Since these effects depend on laser polarization, we developed an active fiber-based retroreflector with a polarization monitor (5). Furthermore, we find that in our case the quantum interference is strongly suppressed. We performed a preliminary measurement of the 2S-6P transition in deuterium, which demonstrates the feasibility of determining this transition frequency with a similar precision as for hydrogen.

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Poster Session 1 / **57**

Towards laser cooling of negative molecular ions

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The AEgIS experiment at CERN's Antiproton Decelerator aims at measuring the gravitational acceleration $\bar{g}$ of antihydrogen ($\bar{H}$) with high precision [1, 2]. A key limitation in these measurements is the $\bar{H}$ temperature: The thermal motion of the $\bar{H}$ atoms blurs their free-fall trajectories and thus limits the achievable $\bar{g}$ precision.

The temperature of antihydrogen, which is formed at AEgIS in a laser-induced charge transfer reaction between positronium and antiprotons ($\bar{p}$), is dominated by the temperature of the antiproton precursors. With the current passive cooling scheme, the achievable $\bar{p}$ temperature is limited to at best tens (but to date a few hundred) kelvin.

Sympathetic cooling of antiprotons through thermalization with co-trapped laser-cooled ions would enable achieving temperatures in the mK range. However, to avoid annihilation, the co-trapped coolant ions must be negatively charged.

The Borealis project at AEgIS aims at realizing Doppler laser cooling of a negative ion. In particular, the diatomic molecular C_2^- ion, a well-suited anion species for laser cooling [3], has been produced, mass-selected and stored in a linear Paul trap [4]. Currently, the capture efficiency of the trap and the lifetime of trapped C_2^- ions are improved and preparations for preliminary in-beam spectroscopic studies are underway.

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Session 8 / **58**

Rydberg atom interferometry for testing the Weak Equivalence Principle with antimatter

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Atom interferometry involving cold ground-state atoms is well established for precisely measuring acceleration due to gravity, g, and testing the Weak Equivalence Principle (WEP) 1. However, because of the short (142 ns) ground-state annihilation lifetime of positronium, to exploit analogous techniques to test antimatter gravity, to complement the 'free-fall' experiments with antihydrogen at CERN [2], and the WEP for this purely leptonic system, it is necessary to excite the atoms to Rydberg states with long lifetimes (>10 μs) [3]. Based upon these considerations, we have developed a scheme to measure acceleration due to gravity by Rydberg-atom interferometry. This uses a technique which is an electric analogue of magnetic Stern-Gerlach interferometry typically performed with paramagnetic ground state atoms [4]. This scheme involves preparing the atoms in superpositions of Rydberg states with different static electric dipole moments, and exerting state-dependent forces on them using inhomogeneous electric fields [5]. The effect of gravity on the evolution of the resulting superposition of momentum states can then be monitored to obtain a value for g. We will

describe the design of this type of Rydberg-atom interferometer and outline how it can be operated to measure g in experiments with helium and, in the longer term, positronium atoms.

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Session 6 / **59**

A new frontier in fundamental physics: precision vibrational spectroscopy of H_2^+

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Molecular hydrogen ions (MHIs) represent a class of bound quantum systems with significant potential for advancing our knowledge in multiple scientific domains, including the determination of fundamental constants, test of quantum physics, and the search for new interparticle forces. Furthermore, the comparison of transitions in MHIs and their antimatter counterparts provides an opportunity for novel tests of CPT invariance 1.

Among the various isotopologues of MHIs, in recent years only heteronuclear HD^+ has been a focus of experimental investigation, yielding significant data on its rovibrational transition frequencies as well as its spin frequencies [2,3,4,5]. In particular, our measurements of two rovibrational transitions provide data on the spin structure consistent with the most precise *ab initio* calculation [4,5].

Expanding the scope of research to include other isotopologues of MHIs is crucial [6], with homonuclear H_2^+ being a valuable choice. However, spectroscopic studies of H_2^+ have historically faced difficulties because of lack of electric-dipole transitions, necessitating the development of alternative spectroscopic approaches. These challenges have prevented the realization of laser spectroscopy of H_2^+ until recently.

We have now succeeded in measuring a rovibrational electric-quadrupole (E2) transition in H_2^+ [7]. While the spectral lines exhibited Doppler broadening, in an additional study we demonstrated the feasibility of Doppler-free E2 spectroscopy, using HD^+ as a test molecule. We achieved unprecedented line resolution of 2.6×10^{12}, improving on a previous demonstration by six orders of magnitude [8].

A characterization of Doppler-free transitions in H_2^+ at metrological level would be a milestone, as it would lead to a spectroscopically determined electron-proton mass ratio. Therefore, our current efforts are focused on implementing Doppler-free vibrational spectroscopy of H_2^+. We will present up-to-date results and their interpretation at the meeting.

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Session 8 / **60**

LEMING - Cold muonium for atomic physics and gravity

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In the LEMING experiment we aspire to carry out next generation laser spectroscopy and gravity experiments using a novel cold atomic beam of muonium (Mu = $\mu^+ + e^-$). The result of a Mu free fall measurement would reveal a clean coupling of gravity to elementary (anti)leptons from the second generation, complementary to all existing probes - normal atoms and recently antihydrogen - where composite hadronic masses dominate the interaction.

To measure the expected nanometer-scaled displacements of Mu trajectories by gravitational acceleration, phase-sensitive methods like atom interferometry is needed. However, state-of-the-art thermal muonium sources were not amenable to produce the contrast and intensity needed for such a measurement.

We recently succeeded in developing a novel cold atomic Mu beam in vacuum using muon conversion in a thin layer of superfluid helium (SFHe), amenable to atom interferometry. Muonium atoms were synthesized and thermalized to below v_t ˜ 0.06 km/s velocities in SFHe, and gained v ˜ 2.2 km/s velocity at the surface in normal direction by transforming the chemical potential to kinetic energy. We report here the synthesis of this high luminosity beam, resulting in ˜10% conversion efficiency of the stopped muons to vacuum muonium. Latest results concerning the atomic interferometer setup and the feasibility studies of the various precision experiments will be also presented.

Poster Session 1 / **61**

Nuclear structure corrections and the helium isotope-shift puzzle from chiral effective field theory

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Measurements of the difference between the squared charge radii of the helion (^{3}He nucleus) and the α-particle (^{4}He nucleus) from ordinary atoms and muonic atoms differ at the level of 3.6 σ. In order to perform these extractions, input from nuclear theory is required. In this work, we present a new analysis of the uncertainties arising from nuclear structure corrections using the framework of chiral effective field theory with modern Bayesian uncertainty quantification techniques. With the new nuclear structure input, the helium isotope-shift puzzle cannot be explained, rather it is reinforced to a 4 σ discrepancy.

Session 8 / **62**

Measurement of the C-forbidden $2\,^3\mathrm{S}_1 \rightarrow 2\,^1\mathrm{P}_1$ transition in positronium

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We report the results of a new measurement of the $2\,^3\mathrm{S}_1 \rightarrow 2\,^1\mathrm{P}_1$ transition (ν_F) in positronium (Ps). This transition, which is strictly forbidden by charge conjugation symmetry (C), can be observed in a magnetic field. Using a pulsed Ps beam we optically generate radiatively metastable $2\,^3\mathrm{S}_1$ atoms, and then drive them to the $2\,^1\mathrm{P}_1$ level in a rectangular waveguide using microwave radiation. Using the same technique, we also measured the C-allowed $2\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_1$ transition (ν_1) in the same waveguide, and used the observed Zeeman shift to determine the local magnetic field strength. The measurements were performed in a range of magnetic fields, making it possible to determine the field-free ν_1 and ν_F transition frequencies, and to set limits on the C-forbidden transition matrix element $|\langle 2\,^1\mathrm{P}_1|H_{CP}|2\,^3\mathrm{P}_1\,\rangle|$.

Session 4 / **63**

Precise Spectroscopy of the Fundamental Vibrational Band in a Trapped Single Molecular Nitrogen Ion

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Precision spectroscopy of dipole-forbidden rotational and vibrational transitions in molecular ions presents a promising avenue for investigating fundamental physical theories, detecting variations in fundamental constants, and establishing new frequency standards. Until recently, achieving the necessary precision has been hindered by the lack of control over molecular ions at the quantum level.

Here, we introduce novel methodologies enabling the preparation of a single molecular ion, specifically N_2^+, in its rovibrational ground state and achieving high-fidelity quantum state detection. Leveraging techniques such as Doppler, Sideband, and EIT laser cooling, coupled with quantum-logic protocols utilizing co-trapped ions, we achieve quantum non-demolition state detection with fidelities exceeding 99%. Our focus now extends to the detection of quadrupole transitions within the fundamental vibrational band S(0). By referencing our spectroscopic measurements to the Swiss primary frequency standard at METAS, we ensure absolute frequency stability, paving the way for precision measurements with an absolute precision on the order of 10^{-15}.

Additionally, these advancements not only push the boundaries of molecular ion spectroscopy but also hold promise for applications in molecular quantum technologies, including the implementation of molecular qubits, mid-IR frequency standards, and high-resolution studies of state-to-state dynamics in chemical reactions.

Poster Session 2 / **64**

Developments of a computational relativistic QED framework for two-spin-1/2-particle systems

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The Bethe–Salpeter (BS) QED wave equation and its equal-time variant [1, 2, 3] are considered for numerical precision computations. If only single-photon instantaneous Coulomb(–Breit) interactions are considered in the interaction kernel, then the equal-time BS equation simplifies to the with-pair Dirac–Coulomb(–Breit) wave equation. Mathematical properties and numerical results are discussed for this linear wave equation and its non-Hermitian Hamiltonian. A numerical basis set approach is presented which is used to converge the with-pair (and no-pair) DC(B) energies to 1:10^9 to 1:10^{12} relative precision for the He atom (& isolectronic ions), H_2, HeH^+, and H_3^+ with clamped nuclei [4 − 10] and for the two-spin-1/2 fermion systems, Ps, Mu, H, and μH [10, 11]. The α fine-structure dependence of the variational energy is in excellent agreement with the relevant non-relativistic QED (nrQED) values up to $\alpha^4 E_\mathrm{h}$ ($m\alpha^6$) and $\alpha^4 \ln\alpha\ E_\mathrm{h}$ ($m\alpha^6 \ln\alpha$) orders. Ongoing work targets a perturbative account for higher-order interaction kernels, retardation and self-energy effects through the equal-time BS equation using the no-pair or the with-pair state as a high-precision reference [12, 13] as a replacement to the non-relativistic reference of nrQED.

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Calculations of the one-loop self-energy correction in one-electron systems with a numerical Green function

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Major progress in spectroscopy of ro-vibrational transitions of hydrogen molecular ions (HMI) has been achieved in the past few years, and the precision of these measurements can still be pushed further. In conjunction with further developments in the theory, this would yield tighter constraints on physics beyond the standard model and improved determinations of fundamental constants.

The theoretical precision is currently limited by the one-loop self-energy correction, which has been so far calculated perturbatively 1. In order to evaluate this quantity in a fully relativistic approach

we need the Dirac Green function of an electron in a two-center Coulomb potential, which is not known in analytic form. A numerical approximation of the Dirac Green function has been developed in our group 2 using the full spectrum of the Dirac equation obtained by a basis set method.

Having in mind the calculation of the one-loop self-energy in HMI, we perform calculations of this QED correction for H-like systems based on the algorithm developed by 3, except that we use a numerical Green function analogous to the one we obtained for HMI. Comparison with previous works that used the known analytical expression of the Dirac Green function [3, 4] allows evaluating the feasibility of extending this approach to HMI.

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Session 6 / **66**

Stringent tests of ab initio QED calculations in the ALPHATRAP experiment

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Quantum electrodynamics (QED) is tested with great precision in small fields by the electron $g-2$ measurement 1. Studying effects as self-energy and vacuum polarization is still of utmost importance due to some unsolved puzzles, as in example the discrepancy in the muon $g-2$ value. Thus, providing better tests of the theory in extreme cases is part of ongoing research. Highly charged ions are of special interest, as the strong electron-nucleus interaction brings forth large QED effects. At the same time, with only a few bound electrons, their simple configuration allows accurate prediction of these effects which can therefore be tested with high precision.
In this contribution, the recent measurements of bound electron g factors in hydrogen-like, lithium-like and boron-like tin are presented together with state-of-the-art theoretical predictions. The measurements were performed in the ALPHATRAP Penning-Trap apparatus, where for each a relative uncertainty of 0.5 parts-per-billion was reached, providing three unique tests of QED theory in the medium-to-high-Z range. In the hydrogen-like case, the measurement provides the most stringent QED test in electronic systems with similar conditions 2. In the lithium- and boron-like systems additionally the contributions due to the relativistic electron-electron interactions can be tested 3.
Alongside the QED tests in extreme fields, first results and future plans on the HD^+ measurement campaign performed at ALPHATRAP, aiming towards high-precision tests of molecular theory, will be discussed. In the apparatus, we have unique capabilities of state-detection, as well as storage times longer than weeks, allowing single ion experiments with high-precision. Details on the recent measurement of the hyperfine structure will be presented along with the plans for high-precision spectroscopy of the rovibrational transitions.
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Session 7 / **67**

Two-loop self-energy correction to the bound-electron g-factor in hydrogenlike ions

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The g-factor of electrons bound in hydrogenlike ions can be measured and calculated with high accuracy. In recent collaborations, the experimental and theoretical g-factors of the bound electron in hydrogenlike $^{3}He^{+}$ and $^{118}Sn^{49+}$ ions were found to be in excellent agreement [1,2]. In the case of Sn, the theoretical uncertainty of the g-factor was limited by QED corrections with two self-energy loops which so far have been calculated only in the framework of a perturbative expansion in $Z\alpha$ 2. The calculation of two-loop self-energy diagrams exactly in $Z\alpha$ will significantly improve the accuracy of the bound-electron g-factor in the high-Z regime. For such an all-order evaluation, the total two-loop self-energy correction needs to be split into the so-called LAL contribution and the F-, M- and P-terms which require different analytical and numerical techniques. In our previous work, we presented numerical results for the LAL contribution and the F-term 3. In this work, we present our calculations of the M- and P-terms which complete the two-loop self-energy calculations and enable improved tests of QED in planned experiments in the near future. These calculations are relevant for the determination of fundamental constants such as the electron mass or the fine-structure constant α as well as searches for physics beyond the standard model.

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Session 3 / **68**

Towards XUV Frequency Comb Spectroscopy of the 1s-2s Transition in He+

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Bound-state quantum electrodynamics (QED) accurately describes the energy levels of hydrogen-like atoms and ions. High-precision laser spectroscopy experiments provide one of the best tests of the theory. The frequency of the narrow 1s-2s transition of atomic hydrogen has been measured with a relative uncertainty of less than 10^{-14}. By combining two spectroscopic measurements of a hydrogen-like system the Rydberg constant and the nuclear charge radius can be determined. The comparison of the physical constants obtained from different combinations of measurements serves as a consistency check for the theory 1. It is interesting to measure different hydrogen-like systems

since they have a higher sensitivity to different contributions of the theory. The measurement of the Lamb shift in muonic hydrogen, for instance, has enhanced sensitivity to the proton radius and gave rise to the proton radius puzzle 2. Another interesting spectroscopic target is the hydrogen-like He^+ ion. Interesting higher-order QED corrections scale with large exponents of the nuclear charge, making measurements in He^+ much more sensitive to these corrections compared to hydrogen. In this talk, we describe our progress towards precision spectroscopy of the 1s-2s two-photon transition in He^+ 3. Ideal conditions for high-precision measurements can be achieved by holding a small number of He^+ ions nearly motionless in the field-free environment of a Paul trap. There, they are sympathetically cooled by co-trapped Be^+ ions. The 1s-2s transition can be directly excited by an extreme-ultraviolet frequency comb at 60.8 nm, which is generated by a high-power infrared frequency comb using high-harmonic generation. After successful excitation to the 2s state, a significant fraction of the He^+ ions will be further ionized to He^{2+} and remain in the Paul trap. Sensitive mass spectrometry using secular excitation will reveal the number of trapped He^{2+} ions and will serve as a single-event sensitive spectroscopy signal.

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Session 5 / **69**

Towards the controlled formation of antiprotonic atoms at AEGIS

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The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEgIS) at CERN's Antimatter Decelerator (AD) is used for the production and study of antimatter bound systems, such as antihydrogen for the gravitational influence on a horizontal beam of cold antihydrogen atoms 1. AEGIS has achieved remarkable performance in trapping antiprotons and successfully demonstrated the pulsed production of Rydberg excited antihydrogen [2,3]. The production process of antihydrogen is achieved through a charge-exchange reaction using laser-excited Rydberg positronium interacting with cold antiprotons stored within a Penning-Malmberg trap.
This technique is currently being adapted for the controlled formation of antiprotonic atoms containing medium-heavy nuclei 4. So far, antiprotonic atoms were formed in beam-on-target experiments, primarily focusing on light systems such as antiprotonic helium [5,6]. Using the charge-exchange procedure developed for antihydrogen production, antiprotonic atoms can be selectively formed in highly excited Rydberg states inside a trapping environment, enabling precision spectroscopy of these systems. The relaxation of the bound antiproton leads to Auger electron and x-ray photon emission, eventually forming a fully or nearly fully stripped nucleus with the bound antiproton. The subsequent annihilation on the nucleus will result in the formation of highly charged nuclear fragments which can be captured within a nested trap. The rapid capture of the highly charged nuclear fragments opens the avenues for new applications and nuclear structure studies 7.
Recent, experiments at AEgIS have successfully demonstrated the trapping of fully stripped nuclear fragments resulting from antiprotons annihilating with residual nitrogen gas in the cryogenic trap. These highly charged fragments were manipulated and identified through a time-of-flight spectroscopy. Furthermore, the ongoing installation of a negative ion source will allow the first co-trapping of negative ions with cold antiprotons for the controlled laser-triggered formation of antiprotonic atoms. These new developments pave the way for precision studies using antiprotonic atoms and exotic highly charged nuclei at AEgIS.
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Session 9 / **70**

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

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The Hyper-mu experiment at PSI aims at the first measurement of the ground state hyperfine splitting in muonic hydrogen (μp) with an accuracy of 1 ppm. Such a measurement would lead to the extraction of the two photon exchange, encoding the proton Zemach radius and polarizability, with an unprecedented relative uncertainty.
Toward the measurement of the ground state hyperfine splitting in μp, we develop a unique pulsed laser system with the aim of delivering 5mJ pulses at a wavelength of 6.8 μm randomly triggered on the detection of muons. We report on the latest laser development within the experiment, the several developments of the detection system that was carried out and the optimization of the experimental parameters to obtain a successful resonance signal.

Session 6 / **71**

Molecular hydrogen ion spectroscopy: prospects for determination of fundamental constants and for theory improvements

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Precision spectroscopy of rovibrational transitions in the HD^+ molecular ion has made significant progress in the past few years, allowing to improve the determination of the proton-electron mass ratio as well as beyond-standard-model physics constraints. In this talk, a few directions for future advances will be discussed, both from an experimental and theoretical point of view.
Firstly, we explore the idea of measuring transitions that involve more excited vibrational levels, whose sensitivity on the nuclear-to-electron mass ratios is either close to zero or positive (rather than negative, as is the case for transitions between low-lying states that have been measured so far). We will show how this allows to bypass, to some extent, the theoretical precision limit associated with uncalculated higher-order QED contributions. As a result, not only the mass ratios, but also the Rydberg constant and nuclear charge radii can in principle be substantially improved by measuring a well-chosen set of transitions 1.
Secondly, we will discuss an area of theory that requires new consideration, namely the relativistic and relativistic-recoil corrections of order α^6. The pure relativistic correction has been so far evaluated only in the adiabatic approximation, whereas one of the contributions to the recoil part was only estimated using results obtained in hydrogen-like atoms. Calculations performed in a full three-body approach will be presented.
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Poster Session 1 / **72**

Hybrid Penning-Linear-Paul trap for ion recapture spectroscopy of hydrogen/antihydrogen in a near-zero bias magnetic trap

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The reason why there is no primordial antimatter in the Universe remains a mystery. Measurements with antimatter 1 show full compatibility with its matter counterparts at high precision and that the antimatter feels Earth's gravitational attraction similarly to matter 3 at low precision.
Antihydrogen (Hbar) is produced by trapping antiprotons and positrons in neighboring wells in a Penning-Malmberg trap and slowing mixing then. An Ioffe-Pritchard octupole magnetic trap superposed to the Penning trap allows the trapping of the produced neutral Hbars with energy below 500 mK 4. Since trapped antiprotons and positrons are needed to create Hbars, a bias magnetic field of ˜1 T is used in the trap region. This high magnetic field adds some systematic uncertainties in comparing the two-photon 1s-2s transition in H and Hbar since accurate measurements with H 5 are performed in a very low magnetic field environment. The precision of the comparison can be improved by trapping hydrogen in the same Hbar trap 68 and repeating the exact measurements with both counterparts, avoiding many systematic uncertainties such as this magnetic field effect, AC Stark shift from the same laser and enhancement cavity operation 9. However, the strong bias magnetic field still affects the transition's lineshape and center. It is possible to ramp down the bias magnetic field and perform the 1s-2s spectroscopy with Hbar's since we can always detect the annihilation of the ionized atoms efficiently. Nevertheless, repeating the exact measurement in a near-zero bias with H is not straightforward since we can not detect the annihilation. If we keep the bias magnetic field, it is possible to recapture a fraction of the ionized H during the spectroscopy 10 by using a weak Penning trap potential, but for a near-zero magnetic field, recapturing the protons can not be accomplished.
Here, we suggest using a hybrid Penning-Linear-Paul trap, using a segmented electrode in the Penning-Malmberg trap to radially confine the ions to perform high precision 1s-2s spectroscopy in H in a near-zero field trap. We will discuss the stability of the recaptured particles in a Linear-Paul trap with a weak magnetic field along the axis, the effect of the electric field on the lifetime of the H/Hbar, lineshape of the transition, the effect of a superposed octupole field to the RF trap, patch potentials, and possible magnetic fields measurements at low fields.
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Poster Session 1 / 73

Calculating the many-potential vacuum polarization density of the Dirac equation in the finite-basis approximation

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Contrary to the muonic atoms case, it is well known that the self-energy correction to the solutions of the Dirac equation dominates vacuum-polarization in electronic atoms. However, having precise results for the latter contribution is crucial to obtaining accurate numerical results on the first-order QED corrections to the Dirac equation. Accounting for the vacuum polarization effect is standardly

done through the inclusion of the Uehling potential 1 $\alpha(Z\alpha)$, and its finite nuclear size correction can be easily incorporated 2. With an increasing nuclear charge Z, or (and) for heavier bound fermions (muons and tauons), it becomes more demanding to include higher-order $\alpha(Z\alpha)^{n\geq 3}$ corrections to the Uehling process, with their corresponding finite nuclear size effects.

In the current work 3, we propose an efficient and accurate method to compute the $\alpha(Z\alpha)^{n\geq 3}$ vacuum polarization density, within the finite basis approximation of the Dirac equation. To prove the functionality of our computational method, we choose to work with the one-electron uranium atom and employ relativistic Gaussian basis functions. In summary, we find that compliance with charge conjugation symmetry is necessary to obtain physical results that are in line with our knowledge of the analytical (exact) problem, as indicated by Salman in 4, in addition to Grant and Quiney in 5. We also note that the final results are in excellent agreement with previous formal analytical (and numerical) evaluations, done by Soff, Mohr, and Plunien in [6, 7]. Our technique can be easily and efficiently implemented in codes that solve the radial Dirac equation in the finite basis set framework and could be employed for atomic problems with arbitrary (radial) nuclear charge distribution. The obtained numerical results of the non-linear vacuum polarization density are, therefore, automatically accounting for the extended nuclear size effect. This method is hence of special importance for atomic problems with nuclear distributions whose analytical expressions of their associated Dirac Green's functions are not in hand or have relatively complicated analytical forms.

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Poster Session 2 / **74**

Casimir forces on atoms in dielectric cavities.

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Several experiments have been performed where cold atoms are being guided through hollow optical fibers. The potential acting on the atom comprises the repulsive potential from the light propagating within the fiber, and the Casimir-Polder potential induced by the vacuum fluctuations. Typically, the Casimir forces acting on atoms are approximated as ones with a flat surfaces —the so called Proximity Force Approximation (PFA). Here we investigate the influence of the surface curvature of the hollow dielectric medium on atoms within it. We present numerical calculations of Casimir-Polder energy for the atom in both a dielectric cylinder and a dielectric sphere. The calculations were performed within the Boundary Element Method (BEM) for concentric dielectric spheres, and coaxial dielectric cylinders. Then, the limit of rarefied dielectric was applied to the inner body which translates the Casimir energy into the interaction potential acting on a single atom within the hollow dielectric medium.

Session 4 / **75**

Accurate theoretical predictions of the rovibrational energy levels of the helium hydride ion

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We present current progress towards accurate theoretical determination of rovibrational energy levels of the helium hydride ion and its isotopologues belonging to its electronic ground state. With the inclusion of nonadiabatic, relativistic and quantum-electrodynamic corrections through Nonadiabatic Perturbation Theory, a theoretical precision better than a few MHz can be achieved. Such an improved knowledge of the rovibrational spectrum should not only facilitate the construction of cosmological models of early Universe chemistry, but also set out a challenge for gas-phase spectrosopic measurements of matching precision.

Poster Session 1 / **76**

Long-range asymptotics of α^3-order QED corrections in H_2 and H_2^+

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Hydrogen molecule and hydrogen molecular ion remain important for test of QED and the determination of fundamental constants. For both of them both the leading (α^3) and next-to-leading (α^4) QED corrections have been computed in the Born-Oppenheimer approximation. We present extremely accurate calculation of the asymptotic behavior of the QED correction for large internuclear distances, including the large-R asymptotics of the Bethe logarithm. While these results are already implemented in the H2spectr code used to predict ro-vibrational levels of the H_2 molecule, but the details of their calculation have never been presented. In particular, the technique of the Bethe logarithm computation via convergence acceleration seem to be new, and might be useful for other atomic and molecular systems.

Session 2 / **77**

Hydrogen spectroscopy as a test of the Standard Model to below 1 part per trillion

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Precision spectroscopy of atomic hydrogen is an important way to test bound-state quantum electrodynamics (QED), one of the building blocks of the Standard Model. In its simplest form, such a test consists of the comparison of a measured transition frequency with its QED prediction, which can be calculated with very high precision for the hydrogen atom. However, these calculations require some input in the form of physical constants, such as the Rydberg constant and the proton radius, both of which are determined to a large degree by (electronic and muonic) hydrogen spectroscopy itself. Therefore, the frequency of at least three different transitions needs to be measured in order to test QED. Furthermore, there are multiple recent, but discrepant measurements of the proton radius, so far precluding QED tests at the highest accuracy.

We have measured the 2S-6P transition in atomic hydrogen with a relative uncertainty of 0.7 parts per trillion (ppt), a six-fold improvement over our previous measurement of the 2S-4P transition 1. This allows us to determine the proton radius and Rydberg constant with an uncertainty below the world-average CODATA-2018 values 2 and sufficient to distinguish between previous, discrepant values for the proton radius by more than 5 σ. Conversely, our measurement, in combination with [2-4], constitutes a test of bound-state QED with an accuracy below 1 ppt, making it one of the most precise tests of the Standard Model.

Here, we discuss the measurement and its analysis in detail, and present the unblinded results and their implications.

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Poster Session 2 / **78**

Electric field sensing in a rectangular waveguide using microwave spectroscopy of Rydberg helium

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Position dependent microwave transitions in Rydberg helium were driven to investigate anomalous systematic effects in the waveguide apparatus used to measure the n = 2 fine structure of positronium 1. The Stark broadening of the resulting line shapes was used to map out stray electric fields 2 along the beam axis and characterize frequency shifts dependent on the microwave propagation direction. As an independent test of the line shape model used to analyse the data, free space microwave spectroscopy was performed in well-defined electric fields external to the waveguide and the results of the two methods have been compared.

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Poster Session 1 / **79**

Characterisation of an energetic beam of metastable positronium atoms for precision spectroscopy

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Precision measurement of positronium, the bound-state of an electron and a positron, can be used to probe fundamental theories and place constraints on physics beyond the standard model 1. Previous spectroscopic studies [2, 3] of the n=2 fine-structure intervals using slow-moving clouds of positronium have achieved only mediocre precision compared with studies of simple atomic systems (e.g. 4), primarily due to line shape distortions 2 caused by microwave reflections 5, and frequency-dependent power variations over the 50 MHz natural line width of the 2S-2P transition. Techniques involving separated fields (e.g. 6) may offer a way forward, although a beam of fast moving atoms in the metastable-state are required 7. In this work I describe the characterisation of an energetic beam of 2^3S_1 positronium atoms8, towards precision measurement of the positronium n=2 fine-structure. Results of initial spectroscopic studies and recent progress are presented.

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Session 8 / **81**

One-dimensional chirp cooling of positronium

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Positronium (Ps), an electron-positron bound system, is pivotal for testing fundamental physics through Quantum Electrodynamics (QED), the most precise theory in physics. To apply extremely accurate transition frequency measurements to Ps with laser precision spectroscopy and minimize systematic errors, it is important to decelerate the gas of Ps. However, the application of laser cooling to Ps has been challenging due to its 142 ns lifetime and significant Doppler broadening.
In this talk, we detail our recent achievement of one-dimensional laser cooling of Ps 1. The experiment employed a specially designed laser that emits a sequence of broadband micro-pulses, with their center frequencies sequentially upshifted [2, 3]. With this novel type of laser, we were able to cool a portion of a Ps gas at 600 K to approximately 1 K in 100 ns. We will compare the cooled Ps velocity distribution to Lindblad equation simulations and consider the impact on future precision spectroscopy. Additionally, we will discuss the prospects of extending this technique to three-dimensional cooling, which could open new avenues in the field of precision spectroscopy for atoms containing antimatter.
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Poster Session 2 / **82**

Hydrogen and deuterium in-beam hyperfine measurements: symmetry tests and prospects for ASACUSA's antihydrogen spectroscopy

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Hyperfine structure measurements on antihydrogen can provide sensitive tests of CPT invariance. The ASACUSA collaboration proposed such experiments on a beam of antihydrogen at the antiproton decelerator of CERN. We benchmark spectroscopy methods and equipment in supporting matter experiments. Beyond the relevance for antihydrogen these measurements can put new or improved constraints on specific coefficients of the so-called standard model extension (SME) even without comparison to antihydrogen.
We have constructed an atomic beam setup for Rabi spectroscopy and performed such measurements for hydrogen at CERN and for deuterium at the Laboratoire Aimé Cotton, Université Paris-Saclay. We obtain constraints, e.g., on the SME non-relativistic (NR) anisotropic proton coefficients $\mathcal{T}_{p010}^{\mathrm{NR,Sun}}$ by hydrogen and at higher fermion momentum power (k=2,4) on $\mathcal{T}_{pk11}^{\mathrm{NR,Sun}}$ by deuterium on the order of 10^{-20} GeV. Determinations of the zero-field hyperfine splitting give agreement with literature (i.e. maser measurements) and the achieved levels of precision around 1 Hz for both atoms present the best values obtained by in-beam spectroscopy in each case. Finally, the relevance of the hydrogen measurements for antihydrogen spectroscopy will be discussed.

Poster Session 2 / **83**

Precision atomic spectroscopy and nuclear properties in $^7Li^+$

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The optical Ramsey technique is used to obtain precise measurements of the hyperfine splittings in the $2\,^3S_1$ and $2\,^3P_J$ states of $^7Li^+$. Together with bound-state quantum electrodynamic theory, the Zemach radius and quadrupole moment of the ^{7}Li nucleus are determined to be $3.35(1)$ fm and $-3.86(5)$ fm^2 respectively, with the quadrupole moment deviating from the recommended value of $-4.00(3)$ fm^2 by 1.75σ. Furthermore, we determine the quadrupole moment ratio of ^{6}Li to ^{7}Li as $0.101(13)$, exhibiting a 6σ deviation from the previous measured value of $0.020161(13)$ by LiF molecular spectroscopy. The results taken together provide a sensitive test of nuclear structure models.

Session 5 / **84**

Constraints on the electric charge of the neutrino and the neutron from atomic physics and cosmology

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TBD

Session 7 / **85**

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

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I will present recent results of a search for a new force between the neutron and the electron. This search is performed using isotope-shift (IS) spectroscopy in calcium ions. IS spectroscopy of atoms and ions has been proposed as a method to search for a fifth fundamental force mediated by a hypothetical dark-matter-candidate boson in the intermediate mass range (100eV to 10MeV). The existence of this new force would cause neutron-number-dependent (and hence, isotope dependent) shifts in atomic transition frequencies. To distinguish these shifts from standard model (SM) shifts (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.

Using an entanglement-enhanced technique to reject common-mode noise, we measure isotope shifts on the 729-nm electric quadrupole transition between pairs of co-trapped calcium ions at 100mHz precision, two orders of magnitude below the previous best measurement. We combine our measurements with IS measurements made by the group of Piet Schmidt on the 570nm transition in Ca14+, and improved nuclear mass measurements made by the group of Klaus Blaum, to produce the first sub-Hz King plot. King plots in calcium had previously remained linear up to the 10Hz level – our improved precision now reveals a large King non-linearity.

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

Session 2 / **86**

Development of (anti)hydrogen fountains and interferometers with the HAICU project at TRIUMF

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Precision comparisons of atomic hydrogen and its antimatter counterpart, antihydrogen, provide stringent tests of fundamental symmetries between matter and antimatter. The most precise measurements of atomic hydrogen properties have traditionally been performed in atomic beams. In contrast, precision measurements of antihydrogen to date have been conducted within a magnetic trap environment, where experimental challenges arise due to the presence of an inhomogeneous field.

To significantly enhance the discovery potential with antihydrogen measurements, we have initiated an ambitious R&D project known as HAICU (Hydrogen-Antihydrogen Infrastructure at Canadian Universities). Located at TRIUMF—Canada's Particle Accelerator Centre in Vancouver—HAICU is utilizing atomic hydrogen to develop the techniques necessary for realizing atomic fountains and interferometers for antimatter. This, in turn, may provide opportunities for novel measurements on hydrogen itself, as no atomic fountains have ever been built for hydrogen.

This talk will provide an overview of the HAICU project, detailing our current progress and discussing the future potential for fountains and interferometers for both hydrogen and antihydrogen.

Session 2 / **87**

Two-loop self-energy without expansion in binding field: present status and recent developments

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The two-loop electron self-energy correction induces one of the two dominant uncertainties in theory of the Lamb shift in hydrogen and He^+ 1. It is currently obtained by extrapolating results of numerical all-order (in $Z\alpha$) calculations for $Z \geq 10$ 2 in combination with available $Z\alpha$-expansion results [3,4]. The present accuracy of the all-order numerical calculations is limited by the convergence of the partial-wave expansion. Recently, methods with improved the partial-wave expansion convergence were developed for the one-loop self-energy problem [5,6]. I will discuss the present status of numerical two-loop calculations in the low-Z region and the generalization of the methods with the improved partial-wave convergence to the two-loop case, and will present preliminary results of improved numerical computations.

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Poster Session 2 / **88**

High-Resolution Spectroscopy of Muonic Lithium - First Steps and Prospects of the QUARTET Experiment

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Precise measurements of absolute nuclear charge radii are crucial ingredients for QED tests and are valuable benchmarks for modern nuclear structure theory 1. Muonic atom spectroscopy is well known as an ideal method to accurately determine the root-mean-square (RMS) radii of the nuclear charge density distribution. By measurements of the 2p-1s transitions of muonic atoms, this technique has already provided precise measurements for the very light (Z<3) as well as heavier nuclei (Z>10) 2. However, a gap for muonic atoms from lithium to neon remains due to the inaccessibility of the relevant energy range (˜20-200 keV) via laser spectroscopy and the insufficient resolution of conventional solid-state detectors for precision measurements.
To address this gap, the QUARTET collaboration employs cryogenic metallic magnetic calorimeters (MMCs), which combine broad-band spectra with record resolving power, to perform spectroscopy of light muonic atoms and to refine the nuclear charge radii of light nuclei from lithium to neon 3.
In October 2023, QUARTET's first test beam time took place at the Paul Scherrer Institute (PSI), where the feasibility of this approach has been demonstrated successfully. This contribution presents the status and plans of the experiment and shows the first broad-band high-resolution spectra of muonic lithium obtained with an MMC.

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Poster Session 1 / 89

Realization of an XUV comb and measurement on its linewidth with frequency comb spectroscopy

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XUV comb has leads to a joint frontier of precision spectroscopy and ultrafast science since its first demonstration in 2005 [1-2]. On one hand, it provides a coherent light source in the XUV region with narrow band width for the first time. This advance paves the way for measuring important atomic transitions in the XUV region [3-4]. On the other hand, ultrafast processes on the attosecond/femtosecond time scale are evolved during high order harmonics generation when the laser intensity inside an enhancement cavity reaches ˜10E13 W/cmˆ2. Thus, ultrafast dynamics can be revealed with high harmonic spectrum, coherence measurements, etc., with the benefit of high repetition rate. In this work, we report on the realization of an XUV comb at Innovation Academy for Precision Measurement Science and Technology, CAS, and the direct frequency comb spectroscopy of a single-photon transition in Xe/NO2 near 148 nm. Our work demonstrates that XUV comb is a potentially powerful toll with narrow linewidth for atomic/molecular spectroscopy in the VUV/XUV region.

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Poster Session 2 / **90**

Muonic Atom Spectroscopy of ^{238}U

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The muX experiment focuses on determining the absolute nuclear charge radius of Radium-226 using muonic atom spectroscopy combined with a novel muon capture method.

Traditionally, muonic atoms are formed by directly stopping muons in the target materials, requiring macroscopic target quantities. However, since radioactive sources are typically available only in microscopic quantities, the muX collaboration developed a new technique. This technique involves a high-pressure hydrogen/deuterium gas mixture in a cell, to capture muons via transfer reactions.

Once captured by the target material, the muons cascade down to their ground state, emitting characteristic X-rays. The energies of these X-rays reveal the muonic energy level scheme, which provides insights into properties such as the nuclear charge radius, quadrupole moment, and magnetic moment.

In the case of Uranium-238 (^{238}U), muonic atom spectroscopy was performed to extract its nuclear properties. The muonic ^{238}U spectrum was analyzed, with a focus on studying cascade behaviors associated with both direct and transfer muon capture. It was observed that direct muon capture demonstrates a preference for transitions from $(n, l = n - 1)$ to $(n - 1, l = n - 2)$ states compared to transfer muon capture, aligning with cascade simulations.

Poster Session 1 / **91**

Time and frequency standards at METAS and their applications for precision measurements

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The Swiss Federal Institute of Metrology METAS and its Photonics, Time and Frequency laboratory are responsible for realizing, maintaining and disseminating the Swiss Coordinated Universal Timescale UTC(CH), and is thus contributing to the realization of UTC at the international level. The realization of UTC(CH) is based on an ensemble of atomic clocks, jointly with our own primary frequency standard FoCS-2 and the appropriate instrumentation and clock algorithms, and provides ultra-stable reference frequencies and timescales, to address a large number of different needs from the industry and for fundamental research. In this poster we will present various applications illustrating how UTC(CH) and the atomic clock ensemble at METAS can support precision physics.
First, we will present the FoCS-2 primary frequency standard 1, a laboratory-size atomic fountain clock that uses a continuous beam of cold caesium atoms to realize the definition of the second as defined in the SI system of units. The use of a continuous instead of pulsed beam of cold cesium is a unique approach, and offers several advantages, such as the absence of the Dick effect and lower atomic density. Nevertheless, the more complex geometry brings certain constraints, such as the need to implement a microwave cavity with two interaction zones, or the presence of residual light scattered lasers used for the preparation and detection of the atoms, which need to be carefully investigated. This clock has been metrologically evaluated, yielding a total relative frequency uncertainty below 2×10^{-15}. Since 2018, FoCS-2 contributes regularly to the realization of TAI, the International Atomic Time.
Second, we will present our phase-stabilized fiber-optic frequency metrology network 2, that currently serves to disseminate the ultra-stable and accurate frequencies generated at METAS to spectroscopy laboratories located at the University of Basel and ETH Zurich. The metrology network covers a total distance of 456 km in the SWITCH fiber network, using a DWDM multiplexing in the L-band. The achieved phase noise levels and link instability will be presented. Further we will show a use case of the disseminated frequency by establishing the SI-traceability of a laser in a remote laboratory.
The implemented realization of UTC(CH) with its atomic clocks, jointly with the frequency dissemination network, is a key infrastructure to provide high performance time and frequency references. Thus it serves the future needs in fundamental metrology, especially towards the implementation of the future new definition of the second based on optical clocks, and to promote new activities in fundamental research, especially in spectroscopy.
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Session 8 / **92**

Laser Cooling of Positronium

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Positronium (Ps), the short-lived bound state of an electron and a positron, exists for only 142 ns in its parallel-spin ground-state configuration (ortho-Ps). It serves as a crucial testing ground for bound-state Quantum Electrodynamics (QED) and for investigating potential violations of the Weak Equivalence Principle for leptons. Existing experiments and proposed schemes have been limited by the broad velocity distribution of traditional Ps sources. To address this, laser Doppler cooling has been proposed for over 30 years but has not been demonstrated before.

In our research, we conduct the first Ps Doppler cooling experiments within the AEgIS (Antimatter Experiment, Gravity, Interferometry, and Spectroscopy) experiment at CERN's Antiproton Decelerator facility 1. We employ a custom-built alexandrite laser to cool ortho-Ps along the 13S-23P transition during its brief lifetime. The laser is specifically designed to meet the experiment's demanding requirements, including pulse energies of several mJ in the UV (243 nm) regime, a bandwidth of about 100 GHz, and a pulse duration of about 100 ns with a fast falling edge. Ps cooling is observed by measuring the Doppler broadening of its 1ˆ3S-3ˆ3P line with a second laser immediately after cooling. The estimated temperature of the ensemble of Ps atoms emitting from a nano-porous positron/Ps conversion target decreases from 380 K to 170 K. This corresponds to a decrease in the transversal component of Ps rms velocity from 54 km/s to 37 km/s.

This methodology paves the way for developing unprecedented Ps sources below 10 K with high intensities. It opens avenues for precision spectroscopy and gravitational experiments with Ps and represents a significant step towards achieving the first Bose-Einstein Condensation of an antimatter species.

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Poster Session 2 / **93**

Progresses towards positronium 1S-2S spectroscopy

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Positronium being a purely leptonic atom provides an ideal test-bench of bound-state QED. Because of its simplicity, any deviation from calculations could hint to new physics beyond the standard model. This poster presents the ongoing experimental progresses made in the laser 1S—2S spectroscopy with the help of a pulsed slow positron beam at ETH.

Poster Session 2 / **94**

One-Particle Operator Representation over Two-Particle Basis Sets for Relativistic QED Computation

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This work is concerned with two(many)-spin-1/2-fermion relativistic quantum mechanics and it is about the construction of one-particle projectors and potentially, one-particle propagators, necessary for quantum-electrodynamics (QED) corrections [1], using an inherently two(many)-particle, 'explicitly correlated' basis representation, necessary for good numerical convergence of the results [2, 3, 4, 5]. It is demonstrated that a faithful representation of the one-particle operators, which appear in intermediate but essential computational steps, can be constructed over a many-particle basis set by accounting for the full Hilbert space, beyond the physically relevant anti-symmetric subspace.

Applications of this development can be foreseen for the computation of quantum-electrodynamics corrections for a correlated relativistic reference state and for high-precision relativistic computations of medium-to-high Z helium-like systems, for which other two-particle projection techniques are unreliable.

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Poster Session 1 / **95**

Towards the self-energy correction of the no-pair Dirac−Coulomb energy for two-electron systems

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Among the leading Quantum Electrodynamical (QED) corrections to atomic-molecular energy levels, the effect of one-loop electron self-energy has proven to be one of the most challenging to compute. There are well-established techniques to calculate it in two extreme cases (for predominantly non-relativistic1 and highly relativistic2 systems, like low-charged and highly charged ions, respectively), but no general method to a correlated relativistic reference state is known.

Finding a self-energy calculating approach generally applicable regardless of the strength of relativistic effects is part of our ongoing research effort to build QED corrections on highly accurate relativistic two-particle wave functions3. Our starting point is the equal-time formulation of the Bethe−Salpeter equation4, and its first approximation, the no-pair Dirac−Coulomb(−Breit) equation; radiative and non-radiative QED corrections are then included perturbatively.

In my poster, I present our current progress towards the calculation of self-energy with a relativistic two-electron wave function. The reference is a no-pair Dirac−Coulomb wave function obtained from an explicitly correlated variational procedure, providing an all-order description of (instantaneous, non-radiative) relativistic effects5.
Working in the framework of the dipole approximation while using such a reference leads to a simple relativistic extension of the so-called Bethe logarithm, and endows the low-frequency part of the self-energy (plus transverse photon exchange) with higher-order binding corrections3. An example calculation is given for the ground state of the helium atom.
Moving beyond the dipole approximation raises several questions concerning the renormalization, the role of negative-energy states and permutational symmetry issues of inner states. A fully numerical renormalization scheme is proposed, reminiscent of partial wave renormalization2. The new challenges and obstacles associated with the relativistic treatment of self energy beyond the dipole approximation are discussed, with preliminary numerical results.

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Poster Session 2 / **96**

Towards XUV Frequency Comb Spectroscopy of the 1s-2s Transition in He+

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Bound-state quantum electrodynamics (QED) accurately describes the energy levels of hydrogen-like atoms and ions. High-precision laser spectroscopy experiments provide one of the best tests of the theory. The frequency of the narrow 1s-2s transition of atomic hydrogen has been measured with a relative uncertainty of less than 10^{-14}. By combining two spectroscopic measurements of a hydrogen-like system the Rydberg constant and the nuclear charge radius can be determined. The comparison of the physical constants obtained from different combinations of measurements serves as a consistency check for the theory 1. It is interesting to measure different hydrogen-like systems since they have a higher sensitivity to different contributions of the theory. The measurement of the Lamb shift in muonic hydrogen, for instance, has enhanced sensitivity to the proton radius and gave rise to the proton radius puzzle 2. Another interesting spectroscopic target is the hydrogen-like He^+ ion. Interesting higher-order QED corrections scale with large exponents of the nuclear charge, making measurements in He^+ much more sensitive to these corrections compared to hydrogen. In this poster, we describe our progress towards precision spectroscopy of the 1s-2s two-photon transition in He^+ 3. Ideal conditions for high-precision measurements can be achieved by holding a small number of He^+ ions nearly motionless in the field-free environment of a Paul trap. There, they are sympathetically cooled by co-trapped Be^+ ions. The 1s-2s transition can be directly excited by an extreme-ultraviolet frequency comb at 60.8 nm, which is generated by a high-power infrared frequency comb using high-harmonic generation. After successful excitation to the 2s state, a significant fraction of the He^+ ions will be further ionized to He^{2+} and remain in the Paul trap. Sensitive mass spectrometry using secular excitation will reveal the number of trapped He^{2+} ions and will serve as a single-event sensitive spectroscopy signal.

Poster Session 1 / **97**

Pair corrections to the no-pair Dirac–Coulomb(–Breit) energy of heliumlike systems

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The equal-time Bethe–Salpeter (Salpeter–Sucher) equation is the exact QED wave equation for a two-fermion system [1, 2, 3, 13, 14]. The equation containing only the instantaneous part of the interaction is the with-pair Dirac–Coulomb(–Breit) equation (wpDC(B)), which includes the double-pair correction to the no-pair DC(B) equation (npDC(B)). The numerical results for these equations can be converged within ppb to ppt relative precision using an explicitly correlated Gaussian (ECG) basis set approach [4]–[12].
While the double-pair correction is a non-hermitian, but 'algebraic'term, which leaves the DC(B) equation linear in energy, the single-pair correction, represented by the irreducible crossed–Coulomb(–Breit) interaction kernel, appears within a complicated, energy dependent operator in the Salpeter–Sucher equation. The inclusion of the crossed–Coulomb(–Breit) and other higher-order irreducible interaction kernels through this term renders the wave equation non-linear in energy.
A novel perturbative approach is therefore being considered for the treatment of these contributions, using the npDC(B) and wpDC(B) results as high-precision relativistic reference energies and wave functions [13, 14]. The results of this new *relativistic* QED (rQED) approach, including the single-pair correction, are expected to serve as a useful comparison to the well established *non-relativistic* QED (nrQED) methodologies, and the highest precision experimental results.

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Poster Session 2 / **98**

Alpha and helion particle nuclear charge determination from precision measurements in quantum degenerate helium

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Precision measurements on calculable systems are widely used for tests of e.g. quantum electrodynamics (QED) calculations, determinations of some of the fundamental constants, and as sensitive probes to search for new physics beyond the standard model. In this context we perform high-precision spectroscopy on the doubly forbidden $2^3S_1 - 2^1S_0$ transition at 1557nm in both ^{3}He and ^{4}He trapped in a magic wavelength optical dipole trap.

We will present our recent measurement in a degenerate Fermi gas of ^{3}He with an accuracy of 170 Hz, and the resulting ^{3}He - ^{4}He isotope shift 1. This measurement enables us to determine the squared charge radius difference between the alpha and helion particle with unprecedented accuracy. Compared to a recent determination of the absolute charge radii from spectroscopy of muonic He+ ions 3, we find a remarkable 3.6 sigma disagreement. Our measurement serves as a check of the consistency of QED theory in helium atoms and of nuclear polarization effects in muonic helium ions.

Currently, we are working on improving the $2^3S_1 - 2^1S_0$ transition in ^{4}He to an accuracy of 50 Hz. Together with our recent ^{3}He measurement, we expect a factor of 2 improvement in the determination

of the squared charge radius difference.

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Poster Session 2 / **99**

Accurately obtaining muonic hydrogen hyperfine splitting from the electronic result

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Using known methods now significantly improvable because of recent advances in the input data, we obtain the currently most accurate calculation of the hyperfine splitting (HFS) in muonic hydrogen. The crucial part of the calculation is the hadronic or proton structure dependent two photon exchange correction, which is calculated in a data driven approach that uses the proton electromagnetic form factors and spin-dependent structure functions as input. One begins with the 12-figure-accurate measurement of the HFS in ordinary hydrogen and obtains the bulk of the muonic hydrogen result by scaling with the reduced mass. The corrections to this scaling are small and calculable with the stated input, and yield uncertainty limits that are much reduced compared those from a stand-alone calculation of muonic hydrogen HFS.

Poster Session 1 / **100**

Regularized relativistic corrections for polyelectronic and polyatomic systems with explicitly correlated Gaussians

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Drachmann's regularization approach is implemented for floating explicitly correlated Gaussians (fECGs) and molecular systems. Earlier applications of Drachmannized relativistic corrections for molecular systems were hindered due to the unknown analytic matrix elements of $1/r_{ix}1/r_{jy}$-type operators with fECGs. In the present work, one of the $1/r$ factors is approximated by a linear combination of Gaussians, which results in calculable integrals. The numerical approach is found to be precise and robust over a range of molecular systems and nuclear configurations, and thus, it opens the route towards an automated evaluation of high-precision relativistic corrections over potential energy surfaces of polyatomic systems. Furthermore, the newly developed integration approach makes it possible to construct the matrix representation of the square of the electronic Hamiltonian relevant for energy lower-bound as well as time-dependent computations of molecular systems with a flexible and high-precision fECG basis representation.

Poster Session 2 / **101**

The ASACUSA-Cusp experiment

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The ASACUSA Cusp collaboration aims to measure the ground-state hyperfine splitting of antihydrogen to a relative precision of parts per million, using a spin polarised antihydrogen beam in a low magnetic field region 1.
The first antihydrogen was successfully synthesised in the ASACUSA-Cusp experiment in 2010 2 by mixing antiprotons and positrons in the so-called Cusp trap, which is a Penning-Malmberg trap with a cusped magnetic field. The principle quantum number (n) distribution was measured 2.7m away from the production region a few years later 3. This measurement revealed that most atoms were produced in high Rydberg states and only a small fraction in lower n-states.
The production rate of antihydrogen increases with lower temperature and high densities of the positron plasma 4. In order to increase the number of antihydrogen atoms produced in the Cusp trap, it was upgraded with a focus on decreasing the temperature of the plasma.
In addition, the positron system was upgraded and a third stage accumulator was added to accumulate several bunches of the buffer gas trap. Pumping out the gases used for trapping and accumulating positrons, which was not possible in the previous design, decreased the contamination of the UHV of the Cusp trap during the transfer of positrons.
This poster will present the upgrades of the positron system and the Cusp trap, as well as results on the on the plasma temperature and density control and the results of last year's antihydrogen run.

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Poster Session 2 / **102**

Low-excitation transport and separation of high-mass-ratio mixed-species ion chains

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We demonstrate low-excitation transport and separation of two-ion crystals consisting of one $^{9}\mathrm{Be}^{+}$ and one $^{40}\mathrm{Ca}^{+}$ ion, with a high mass ratio of 4.4. The full separation involves transport of the mixed-species chain, splitting each ion into separate potential wells, and then transport of each ion prior to detection. We find the high mass ratio makes the protocol sensitive to mode crossings between axial and radial modes, as well as to uncontrolled radial electric fields that induce mass-dependent twists of the ion chain, which initially gave excitations $\bar{n} \gg 10$. By controlling these stages, we achieve excitation as low as $\bar{n} = 1.40 \pm 0.08$ phonons for the calcium ion and $\bar{n} = 1.44 \pm 0.09$ phonons for the beryllium ion. Separation and transport of mixed-species chains are key elements of the QCCD architecture, and may also be applicable to quantum-logic-based spectroscopy of exotic species.

Poster Session 2 / 103

Free-space microwave spectroscopy of the positronium $n = 2$ fine structure intervals

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The positronium (Ps) $n = 2$ fine structure intervals can be used to test bound-state quantum electrodynamics (QED) 1, with current measurements using microwave waveguides at a precision of 100 parts-per-million (ppm) 2. However, the 10 mm scale of waveguides in the GHz regime results in short transit times and low phase acceptance of the fast and divergent Ps beam. We therefore use free-space radiation in our experiment to target the entire Ps ensemble and minimise transit-time broadening, also greatly simplifying the required vacuum setup.

Linearly polarised microwave radiation was applied using a horn antenna placed outside the vacuum chamber containing metastable Ps* atoms. The >50 MHz wide $2\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$ $(J = 1, 2)$ transitions were driven in two separate experiments. We measured apparent shifts in the $J = 2$ transition which varied by up to 500 ppm 3. This was due to reflections of the microwave radiation from the apparatus causing frequency dependent field strength. We also observed the excitation of polarisation-forbidden excitation pathways of the $J = 1$ transition due to reflections causing incomplete polarisation of the microwave radiation.

These effects make precision measurements of broad energy intervals using free-space microwave radiation challenging, but offer insight into effects which may not be observed in narrower resonances (e.g. 4) until a higher level of precision is achieved.

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Poster Session 2 / 104

The S-wave H^- resonances by Lagrange-mesh methods

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The Lagrange-mesh method in perimetric coordinates is an efficient and rather simple method to study three-body Coulomb systems such as He, H^-, Ps^-, or H_2^+ 1, as well as quasibound states of exotic Coulomb atoms such as $He^+\bar{p}$, $\bar{p}H$, and $He^+\pi^-$ [2-4]. Recently, two extensions of the method have been developed to properly describe resonant states [3-7]: one based on the complex scaling method and the other on the Kohn variational principle. In the latter case, scattering can also be studied. In this contribution, these methods will be applied to study the S-wave resonance states of the hydrogen ion. In addition to the resonance parameters, the S-wave H+e^- elastic phase shifts, obtained with the Lagrange-mesh method combined to the Kohn variational principle, will be also presented.

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Poster Session 2 / **105**

The Hydrogen 1S-3S Direct Frequency Comb Spectroscopy Experiment - Overview and Update of the Detection Scheme

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Precision spectroscopy of atomic hydrogen is a powerful tool to test QED theory as energy transitions can be measured, calculated and subsequently compared on a high level of precision. As free parameters in the theory, the Rydberg constant R_∞ and the proton charge radius r_p remain to be determined by spectroscopy 3, since other parameters entering the calculation, such as the fine structure constant α or the electron-proton mass ratio m_e/m_p, are given very precisely by other experiments, e.g. atom interferometry or Penning trap experiments respectively.
Thus, two transition measurements in hydrogen are required to fix R_∞ and r_p and more to check for consistency. Adding a contribution to that quest, the 1S-3S experiment at MPQ in Garching delivered its first result in 2020 with a fractional uncertainty of 10^{-13} 2. Since the 1S-3S transition was also measured by colleagues at the Laboratoire Kastler Brossel in Paris 1, with a value currently different to the MPQ measurement by 2.1 standard deviations, it is an experiment of particular importance as it provides the only transition measurement that has been conducted redundantly by two groups with independent systematics. Strongly hinting to unknown experimental issues, this discrepancy motivates the further improvement of the experimental setup towards a lower uncertainty measurement. In this poster an overview of the current setup of the spectrometer is given, with a focus on the characteristics of the detector that is used for fluorescence detection from the excited atoms. It also presents the current development stage of a new detector together with an outlook of improvements expected from the planned modifications.

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Session 4 / **106**

Laser excitation of the low-energy nuclear transition in 229Th

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We report the first direct laser excitation of the Th-229 nuclear transition in Th-doped CaF2 crystals using a tabletop tunable laser system. The Th:CaF2 crystals are grown at TU Wien with up to 5×10^{18} cm^{-3} Th-229 concentration, and a VUV laser system developed at PTB, that provides a spectral photon flux of more than 2×10^4 photons/(s Hz).
A resonance fluorescence signal is observed in two crystals with different Th-229 dopant concentrations, while it is absent in a control experiment using Th-232. The nuclear resonance for the Th^{4+} ions in Th:CaF2 is measured at the wavelength 148.3821(5) nm, frequency 2020.409(7) THz, and the fluorescence lifetime in the crystal is 630(15) s. Because of the higher density of photon states in the dielectric optical medium, the measured spontaneous M1 decay rate is expected to be enhanced relative to the rate in vacuum by a factor n^3 where n is the refractive index. Applying this correction, the measured radiative lifetime of 630(15) s corresponds to an isomer half-life in vacuum of 1740(50) s.
These results pave the way towards high-resolution Th-229 nuclear laser spectroscopy and realizing optical nuclear clocks.

Poster Session 1 / 109

Status of laser spectroscopy of metastable antiprotonic helium atoms at CERN

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The ASACUSA collaboration carries out laser spectroscopy of metastable antiprotonic helium atoms ($\bar{p}He^+ = \bar{p} + He^{2+} + e^-$) at CERN's Antiproton Decelerator facility [1-5]. This is a three-body Coulomb system composed of a helium nucleus, an electron, and orbital antiproton. CERN has recently commissioned the ELENA ring, which produced cooled beams of antiprotons with >100 times higher emittance than before. We propose to utilize the unprecedented high-quality beam of this new facility and the latest laser metrology techniques to carry out sub-Doppler two-photon laser spectroscopy of narrow resonances of $\bar{p}$He$^+$ with a far higher precision than before. These experiments allow the antiproton-to-electron mass ratio to be determined 4. Limits may be established on exotic forces that may arise between the constituent particles. A new antiproton beamline with several special features was constructed and commissioned; a sophisticated laser system is now being developed.

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Session 2 / **110**

How to trap atomic hydrogen without laser cooling

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Atomic hydrogen has an ideal level scheme for an optical clock. Since there is no 1P state, the 2S state can neither decay nor be excited with a single photon dipole transition, at least not in a field-free environment. This has three important advantages: The lifetime of the 2S is very long leading to natural line width of 1.3Hz. This is a good value for an optical clock. Because the 1S-2S clock transition at 2466THz is excited with two photons, the required laser operates at 243nm rather than at 121.5nm (Lyman-alpha). Moreover, the two-photon excitation can be arranged such that it is free of the Doppler effect in first order. This also implies that only moderately low temperatures and no strong confinement (Lamb-Dicke regime) of the trapped atoms is required. The magic wavelength 1 for the 1S-2S transition is at a convenient value of 515nm 2. High power narrow band lasers are readily available by frequency doubled Yb-based lasers.

Obviously, the main showstopper is the required Lyman-alpha laser for cooling. Cooling atomic hydrogen that is already trapped has been achieved with pulsed Lyman-alpha lasers. These are not too difficult to realize with a low repetition rate and hence a large pulse energy to enhance the required non-linear frequency conversion. For loading the trap, a continuous wave or a high repetition rate laser with sufficient power would be required. This has not been possible so far. While magnetic trapping of hydrogen and anti-hydrogen have been demonstrated, we do not like them for precision experiments because of the large Zeeman shifts (Bohr's magneton is 14GHz/Tesla). Moreover, due to the low atomic mass and the large photon momentum, cooling on the 1S-2P transition would be rather inefficient with the Doppler and recoil limit as high as 2.39mK and 1.29mK respectively.

A number of proposals have been published to circumvent the Lyman-alpha laser [3,4,5,6,7]. You should not miss this presentation if you want to find out about our approach. It uses the selection of the slow tail of velocities from a thermal beam and the photon recoil by an induced decay of the meta-stable 2S state inside an optical dipole trap. In contrast to laser cooling, this method works the better the lower the atomic mass and the larger the photon recoil gets. Besides of improving the measured transition frequencies, trapped atomic hydrogen could eventually be the motivation to redefine the SI second in terms of the Rydberg constant. This would remove the last remaining object in the definitions of the SI which is otherwise based defined values of physical constants (c, h and e).

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