PSAS'2024 - International Conference on Precision Physics of Simple Atomic Systems

Monday, 10 June 2024 - Friday, 14 June 2024

ETH Zurich- Hönggerberg Campus

Programme

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Monday, 10 June 2024

Registration and Coffee (09:00 - 10:00)

Welcome (10:00 - 10:20)

Session 1 (10:20 - 12:15)

[19] Precision mass ratio measurements of light ions at Florida State University (10:20)

Presenter: MYERS, Edmund (Florida State University)

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 ^{4}He^{+}, and the discrepancy between the two most precise literature values for the atomic mass of ^{4}He.

[53] Penning Trap Measurement of the $^{3}\mathrm{He}$ Mass (10:55)

Presenter: BEZRODNOVA, Olesia (Max-Planck-Institute für Kernphysik, Heidelberg)

The masses of lightest nuclei form a network of parameters used in fundamental physics. The mass difference of T and $^{3}\mathrm{He}$, 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, $^{4}\mathrm{He}$, 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, $^{4}\mathrm{He}$ [3]. This contribution presents the preliminary results of the $^{3}\mathrm{He}$ mass measurement campaign, aimed at resolving the discrepancy among the literature values known as the "Light Ion Mass Puzzle". [1] F. Heisse $\textit{et al}$., Phys. Rev. A $\textbf{100}$, 022518 (2019) [2] S. Rau $\textit{et al}$., Nature $\textbf{585}$, 43–47 (2020) [3] S. Sasidharan $\textit{et al}$., Phys. Rev. Lett. $\textbf{131}$, 093201 (2023)

[16] Precise Zeeman structure measurements of light ions at μTEx (11:20)

Presenter: KAISER, Annabelle (Max-Planck-Institut für Kernphysik)

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. [1] A. Mooser *et al*., J. Phys.: Conf. Ser 1138, 012-004 (2018) [2] A. Schneider *et al*., Nature 606, 878-883 (2022) [3] S. Dickopf *et al*., to be submitted

[35] Laserspectroscopic determination of the nuclear charge radii of $^{12,13}\mathrm{C}$ (11:45)

Presenter: MÜLLER, Patrick (Technische Universitaet Darmstadt (DE))

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 $\delta\!R_\mathrm{C}$, 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}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. This project is supported by DFG (Project-ID 279384907 - SFB 1245). [1] V. A. Yerokhin *et al.*, Phys. Rev. A **106**, 022815 (2022) [2] P. Imgram *et al.*, Phys. Rev. Lett. **131**, 243001 (2023)

Lunch break at Bellavista (12:15 - 14:00)

Session 2 (14:00 - 15:45)

[8] Metrology of Rydberg-Stark states in the hydrogen atom (14:00)

Presenter: SCHEIDEGGER, Simon (ETH Zurich/ JILA)

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, \pm2$) 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. [1] S. Scheidegger *et al.*, Phys. Rev. A **108**, 042803 (2023). [2] S. Scheidegger and F. Merkt, Phys. Rev. Lett. (in press). [3] N. Bezginov *et al.*, Science **365**, 1007 (2019).

[77] Hydrogen spectroscopy as a test of the Standard Model to below 1 part per trillion (14:30)

Presenter: MAISENBACHER, Lothar (University of California, Berkeley)

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. [1] A. Beyer, L. Maisenbacher, A. Matveev et al., Science 358, 79 (2017). [2] E. Tiesinga et al., Rev. of Mod. Phys. 93, 025010 (2021). [3] C. G. Parthey et al., Phys. Rev. Lett. 107, 203001 (2011). [4] A. Antognini et al., Science 339, 417 (2013).

[56] Precision spectroscopy of the 2S-6P transition in atomic deuterium (15:00)

Presenter: WIRTHL, Vitaly

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.][1] 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. References (1) R. Pohl et al., Metrologia 54, L1 (2017) (2) R. Pohl et al., Science 353, 669–673 (2016) (3) A. Brandt et al., Phys. Rev. Lett 128, 023001 (2022) (4) Th. Udem et al., Ann. Phys. 531, 1900044 (2019) (5) V. Wirthl et al., Opt. Express 29(5), 7024-7048 (2021) [1]: https://ibb.co/Gkr0gHs

[87] Two-loop self-energy without expansion in binding field: present status and recent developments (15:20)

Presenter: YEROKHIN, Vladimir (Max Planck Institute for Nuclear Physics)

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 $Z\ge 10$ [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. [1] E. Tiesinga, P. J. Mohr, D. B. Newell, and B. N. Taylor, Rev. Mod. Phys. 93, 025010 (2021). [2] V. A. Yerokhin, Phys. Rev. A 80, 040501(R) (2009). [3] K. Pachucki and U. D. Jentschura, Phys. Rev. Lett. 91, 113005 (2003). [4] S. G. Karshenboim, A. Ozawa, and V. G. Ivanov, Phys. Rev. A 100, 032515 (2019). [5] V. A. Yerokhin, K. Pachucki, and V. M. Shabaev, Phys. Rev. A 72, 042502 (2005). [6] J. Sapirstein, K. T. Cheng, Phys. Rev. A 108, 042804 (2023).

Coffe break (15:45 - 16:15)

Session 2 (16:15 - 17:55)

[110] How to trap atomic hydrogen without laser cooling (16:15)

Presenter: UDEM, Thomas

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 availa-ble 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 would like to avoid strong magnetic fields in 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 better the lower the atomic mass and the larger the photon recoil. 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). [1] H.Katori, Proceedings of the 6th Symposium on Frequency Standards and Metrology, University of St Andrews, Fife, Scotland 9–14 September 2001. [2] C.M.Adhikari, A.Kawasaki, and U.D.Jentschura, Phys. Rev. A 94, 032510 (2016). [3] R.deCarvalho, N.Brahms, B.Newman, J.M.Doyle, D.Kleppner, and T.Greytak, Can. J. Phys. 83, 293 (2005). [4] I.C.Lane, Phys. Rev. A 92, 022511 (2015). [5] R.Côté, M.J.Jamieson, Z-C.Yan, N.Geum, G.H.Jeung, and A.Dalgarno, Phys. Rev. Lett. 84, 2806 (2000). [6] S.F.Vázquez-Carson, Q.Sun, J.Dai, D.Mitra, and T.Zelevinsky, New J. Phys. 24 083006 (2022). [7] S.A.Jones, New J. Phys. 24 023016 (2022).

[86] Development of (anti)hydrogen fountains and interferometers with the HAICU project at TRIUMF (16:45)

Presenter: FUJIWARA, Makoto (TRIUMF (CA))

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.

[5] Low energy hydrogen anions source for matter/antimatter precision experiments (17:15)

Presenter: OLIVEIRA DE ARAUJO AZEVEDO, Levi (Federal University of Rio de Janeiro (BR))

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. [1] - Azevedo, L.O.A., Costa, R.J.S., Wolff, W. et al. Adaptable platform for trapped cold electrons, hydrogen and lithium anions and cations. Commun Phys6, 112 (2023). [2] - Sacramento, R. L. et al. Matrix Isolation Sublimation: an apparatus for producing cryogenic beams of atoms and molecules. Rev. Sci. Instrum.86, 073109 (2015). [3] - Cesar, C. L. A sensitive detection method for high resolution spectroscopy of trapped antihydrogen, hydrogen and other trapped species. J. Phys. B49, 074001 (2016). [4] - Ahmadi, M. et al. Characterization of the 1S-2S transition in antihydrogen. Nature557, 71 (2018).

[52] GRASIAN: Improved measurements with cold hydrogen and deuterium for the forthcoming first demonstration of gravitational quantum states of atoms (17:35)

Presenter: KILLIAN, Carina (Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, Kegelgasse 27, Vienna, 1030, Austria)

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.

<u>Poster Session 1</u> (18:00 - 20:00)

Tuesday, 11 June 2024

Session 3 (09:00 - 10:20)

[25] Hyperfine structure calculations in hydrogenlike and heliumlike atoms (09:00)

Presenter: Dr PATKÓŠ, Vojtěch (Charles University)

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.

[10] Finite nuclear mass correction to the hyperfine splitting in hydrogenic systems (09:25)

Presenter: Prof. PACHUCKI, Krzysztof

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.

[24] Bound state energy levels from trace anomaly (09:50)

Presenter: Prof. EIDES, Michael (University of Kentucky)

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

Coffee break (10:20 - 10:50)

Session 3 (10:50 - 12:30)

[31] Precision spectroscopy of helium atoms (10:50)

Presenter: Dr SUN, Yu

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 [1] X. Zheng, Y. R. Sun, J.-J. Chen, W. Jiang, K. Pachucki, and S.-M. Hu. Phys. Rev. Lett., 118:063001, Feb 2017. [2] X. Zheng, Y. R. Sun, J.-J. Chen, W. Jiang, K. Pachucki, and S.-M. Hu. Phys. Rev. Lett., 119:263002, Dec 2017. [3]J.-J.Chen, Y.R.Sun, J.-L.Wen, and S.-M.Hu Phys.Rev.A,101:053824(2020) [4]Jin-Lu Wen, Jia-Dong Tang, Jun-Feng Dong, Xiao-Jiao Du, Shui-Ming Hu and Y.R.Sun, Phys.Rev.A,107,042811(2023) [5] X. Zheng, Y. R. Sun, J.-J. Chen, J.-L. Wen, and S.-M. Hu. Phys. Rev. A, 99:032506, Mar 2019

[17] Precision spectroscopy of Rydberg states in ^{4}He and ^{3}He (11:15)

Presenter: CLAUSEN, Gloria (ETH Zürich)

The metastable He ((1s)^1(2s)^1) atom in its singlet (^{1}S$_0$) or triplet (^{3}S$_1$) 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 $2\,^1$S$_0$ 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 $3\,^3$D ← 2 ^{3}S [3] and $3\,^3$D ← 2 ^{3}P [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 $2\,^3$S$_1$ state of ^{4}He via the measurement of transitions from the $2\,^3$S$_1$ 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 $2\,^3$S$_1$ 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$^\mathrm{st}$-order Doppler shift to enable Doppler-free spectroscopy. We illustrate its power with a new determination of the ionization energy of $2\,^3$S$_1$ 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 ^{3}He^{+2} and ^{4}He^{+2} nuclei. $[1]$ G. Clausen *et al*., Phys. Rev. Lett. **127**, 093001 (2021). $[2]$ V. Patkóš *et al*., Phys. Rev. A. **103**, 042809 (2021). $[3]$ C. Dorrer *et al*., Phys. Rev. Lett. **78**, 3658 (1997). $[4]$ P.-L. Luo *et al*., Phys. Rev. A. **94**, 062507 (2016). $[5]$ V. A. Yerokhin *et al*., Eur. Phys. J. D. **76**, 142 (2022). $[6]$ V. A. Yerokhin *et al*., Phys. Rev. A. **107**, 012810 (2023).

[68] Towards XUV Frequency Comb Spectroscopy of the 1s-2s Transition in He+ (11:40)

Presenter: EGLI, Florian (Max Planck Institute of Quantum Optics)

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. [1] T. Udem Nature Phys 14, 632 (2018) [2] R. Pohl et al. Nature 466, 213 (2010) [3] J. Moreno et al. Eur. Phys. J. D 77, 67 (2023)

[27] Precision Measurement of Vibrational Quanta in Tritium Hydride (12:00)

Presenter: HERMANN, Valentin (IAP/TLK)

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.

Lunch break at Bellavista (12:30 - 14:00)

Session 4 (14:15 - 15:35)

[13] Precision measurements on the (2-0) quadrupole transitions in H_2 (14:15)

Presenter: UBACHS, Wim (VU University Amsterdam)

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]. (1) W. Ubachs, J.C.J. Koelemeij, K.S.E. Eikema, E.J. Salumbides, J. Mol. Spectr. 320, 1-12 (2016). (2) F.M.J. Cozijn, P. Dupre, E.J. Salumbides, K.S.E. Eikema, W. Ubachs, Phys. Rev. Lett. 120, 153002 (2018). (3) L.-G. Tao, A.-W. Liu, K. Pachucki, J. Komasa, Y. R. Sun, J. Wang, and S.-M. Hu, Phys. Rev. Lett. 120, 153001 (2018). (4) F.M.J. Cozijn, M.L. Diouf, W. Ubachs, V. Hermann, M. Schloesser, Phys. Rev. Lett. (2024) in press. (5) F.M.J. Cozijn, M.L. Diouf, W. Ubachs, Phys. Rev. Lett. 131, 073001 (2023) (6) J. L. Hall, C. J. Bordé, and K. Uehara, Phys. Rev. Lett. 37, 1339 (1976). (7) M.L. Diouf, F.M.J. Cozijn, W. Ubachs, Mol. Phys. e2304101 (2024).

[63] Precise Spectroscopy of the Fundamental Vibrational Band in a Trapped Single Molecular Nitrogen Ion (14:45)

Presenter: DIOUF, Meissa

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.

[75] Accurate theoretical predictions of the rovibrational energy levels of the helium hydride ion (15:10)

Presenter: SILKOWSKI, Michal (Adam Mickiewicz University, Poznań, Poland)

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.

<u>Coffee break</u> (15:35 - 16:05)

<u>Session 4</u> (16:05 - 17:10)

[106] Laser excitation of the low-energy nuclear transition in 229Th (16:05)

Presenter: OKHAPKIN, Maksim (PTB)

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.

[46] Tabletop particle physics and cosmology with precision quantum-logic spectroscopy (16:40)

Presenter: LEIBRANDT, David (UCLA)

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.

Wednesday, 12 June 2024

Session 5 (09:00 - 10:15)

[84] Constraints on the electric charge of the neutrino and the neutron from atomic physics and cosmology (09:00)

Presenter: KARSHENBOYM, Savely (LMU, MPQ, Pulkovo)
TBD

[30] Measuring the neutron electric charge with time-of-flight grating interferometry (09:25)

Presenter: PERSOZ, Marc
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

[34] The neutron lifetime experiment τSPECT (09:50)

Presenter: RIES, Dieter Achim
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.

Coffee break (10:15 - 10:45)

Session 5 (10:45 - 12:30)

[9] Antihydrogen laser spectroscopy to 13 significant figures and beyond (10:45)

Presenter: LENZ CESAR, Claudio (Federal University of Rio de Janeiro (BR))
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.

[40] Precision measurements on protons and antiprotons in the BASE collaboration (11:20)

Presenter: SMORRA, Christian (Heinrich Heine University Dusseldorf (DE))
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. [1] M. J. Borchert et al., Nature 601, 53 (2022). [2] G. Schneider et al., Science 358, 1081 (2017). [3] C. Smorra et al., Nature 550, 371 (2017). [4] M. A. Bohman et al., Nature 596, 514 (2021). [5] J. M. Cornejo et al., Physical Review Research 5,

033226 (2023). [6] C. Smorra et al., Rev. Sci. Instr. 94, 113201 (2023).

[69] Towards the controlled formation of antiprotonic atoms at AEGIS (11:50)

Presenter: PARNEFJORD GUSTAFSSON, Fredrik Olof Andre (CERN)

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. [1] M. Doser et al. 2012 Class. Quantum Grav. 29 184009 [2] D. Krasnicky et al. 2016 Phys. Rev. A 94 022714 [3] C. Amsler et al. 2021 Commun. Phys. 4 19 [4] Doser, M. Progress in Particle and Nuclear Physics (2022): 103964. [5] Hori, Masaki, et al. PRL 87.9 (2001): 093401. [6] Sótér, Anna, et al. Nature 603.7901 (2022): 411-415. [7] Kornakov, G., et al. Phys. Rev. C 107.3 (2023): 034314.

[26] Production of a 6 keV antihydrogen beam in the GBAR experiment (12:10)

Presenter: BLUMER, Philipp Peter (ETH Zurich (CH))

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 $\mathrm{\overline{H}}$ in Earth's gravitational field. The main principle is to first produce an antihydrogen ion $\mathrm{\overline{H}^+}$ and sympathetically cool it with $\mathrm{Be^+}$ in a Paul trap to $\mathrm{\mu K}$ temperature. The excess positron is then photodetached using a $1640\,\mathrm{nm}$ laser and the now neutral anti-atom experiences a classical free fall. By measuring the time of flight and the annihilation position of the $\mathrm{\overline{H}}$ we want to measure its acceleration with a precision of 1% in a first phase. During the production of the $\mathrm{\overline{H}^+}$, $\mathrm{\overline{H}}$ 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 $6~\mathrm{keV}~\mathrm{\overline{H}}$, a milestone for the experiment, as well as the status and future prospects of GBAR [GBAR, EPJC 83, 1004 (2023)].

Lunch break (Bellavista) (12:30 - 14:00)

Session 6 (14:00 - 15:45)

[59] A new frontier in fundamental physics: precision vibrational spectroscopy of H$_2^+$ (14:00)

Presenter: ALIGHANBARI, Soroosh (Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf)

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. *Funding was provided by the European Research Council (ERC) under the EU's Horizon 2020 research and innovation programme (grant agreement No. 786306, ``PREMOL”) and from both the DFG and the state of North-Rhine-Westphalia (Grant Nos. INST-208/774-1 FUGG and INST-208/796-1 FUGG).* [1] E.G. Myers, Phys. Rev. A 98, 010101 (2018). [2] S. Alighanbari, et al. Nature 581, 152 (2020). [3] S. Patra, et al. Science 369, 1238 (2020). [4] I.V. Kortunov, et al. Nat. Phys. 17, 569 (2021). [5] S. Alighanbari, et al. Nat. Phys. 19, 1263 (2023). [6] S. Schiller and J.-Ph. Karr, to appear in Phys. Rev. A (2024). [7] M.R. Schenkel, et al. Nat. Phys. (2024). https://doi.org/10.1038/s41567-023-02320-z [8] M. Germann, et al. Nat. Phys. 10, 820 (2014).

[71] Molecular hydrogen ion spectroscopy: prospects for determination of fundamental constants and for theory improvements (14:25)

Presenter: KARR, Jean-Philippe (Laboratoire Kastler Brossel (FR))

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 $□\alpha^6$. 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. [1] S. Schiller and J.-Ph. Karr, accepted for publication in Phys. Rev. A.

[42] Quantum Logic Spectroscopy of the Hydrogen Molecular Ion (14:50)

Presenter: HOLZAPFEL, David

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

[18] Spin-Rovibrational Structure of the Molecular Hydrogen Ion from Spectroscopy of Rydberg States (15:15)

Presenter: DORAN, Ioana (ETH Zurich)

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 $-R_{\textrm{H}_2}/n^2$ 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. [1] V. I. Korobov et al., Phys. Rev. Lett. 118, 233001 (2017). [2] G. Herzberg and Ch. Jungen, J. Mol. Spectrosc. 41, 425 (1972). [3] M. Beyer et al., Phys. Rev. Lett. 123, 163002 (2019). [4] I. Doran et al., Phys. Rev. Lett. 132, 073001 (2024). [5] N. Hölsch et al., J. Mol. Spectrosc. 387, 111648 (2022).

Coffee break (15:45 - 16:15)

Session 6 (16:15 - 18:00)

[41] Rovibrational energy levels of the hydrogen molecule and its isotopologues from relativistic nonadiabatic calculations (16:15)

Presenter: KOMASA, Jacek (Adam Mickiewicz University in Poznań, Poland)

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.

[66] Stringent tests of ab initio QED calculations in the ALPHATRAP experiment (16:40)

Presenter: MORGNER, Jonathan (Max-Planck-Institut für Kernphysik, Heidelberg)

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. [1] X. Fan, *et al.*, PRL **130**, 071801 (2023), [2] J. Morgner, *et al.*, Nature **622**, 53–57 (2023), [3] J. Morgner, *et al.*, in preparation.

[38] Cavity-enhanced spectroscopy of $\rm \mathbf{H_2}$ in a deep cryogenic regime (17:05)

Presenter: STANKIEWICZ, Kamil (Nicolaus Copernicus University)

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 $\rm H_2$ 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 $\rm 10^{-6}~cm^{-1}$, our system allows for testing of the quantum electrodynamics (QED) corrections for $\rm H_2$ at the fifth significant digit of the QED correction [2-3]. By saturating the very weak quadrupole transitions in $\rm H_2$ 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. [1] M. Słowiński, M. Makowski, K. L. Sołtys, K. Stankiewicz, S. Wójtewicz, D. Lisak, M. Piwiński, P. Wcisło, Rev. Sci. Instrum. 93, 115003 (2022) [2] J. Komasa, M. Puchalski, P. Czachorowski, G. Łach, and K. Pachucki, Phys. Rev. A 100, 032519 (2019) [3] P. Czachorowski, M. Puchalski, J. Komasa, and K. Pachucki, Phys. Rev. A 98, 052506 (2018)

Poster Session 2 (18:00 - 20:00)

Thursday, 13 June 2024

Session 7 (09:00 - 10:20)

[85] Searching for a fifth fundamental force using isotope-shift spectroscopy of trapped ions (09:00)

Presenter: Dr PRADO LOPES AUDE CRAIK, Diana (ETH Zürich)

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.

[32] Hyper-EBIT: A source for heavy highly charged ions (09:30)

Presenter: Ms KULANGARA THOUTTUNGAL GEORGE, Athulya (Max-Planck-Institut für Kernphysik, Heidelberg)

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. [1]S. Sturm et al., Eur. Phys. J. Spec. Top. 227, 1425–1491 (2019) [2]J. Morgner, et al., Nature 622, 53–57 (2023)

[33] Latest results and status update from the Fermilab Muon g-2 experiment (09:55)

Presenter: QURESHI, Mohammad Ubaidullah Hassan (Johannes Gutenberg University Mainz)

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.

Coffee break (10:20 - 10:50)

Session 7 (10:50 - 12:20)

[39] Testing quantum electrodynamics in extreme fields using helium-like uranium (10:50)

Presenter: TRASSINELLI, Martino (CNRS, Sorbonne Université, Institut des NanoSciences de Paris, France)

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 $2p_{3/2} \to 2s_{1/2}$ 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. [1] R. Loetzsch et al., *Nature* **625**, 673-678 (2024).

[36] Quantum Electrodynamics and Quantum Cyclotron Energy Levels (11:25)

Presenter: JENTSCHURA, Ulrich (Missouri University of Science and Technology)

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.

Lunch break (Bellavista) (12:30 - 14:15)

Session 8 (14:15 - 15:30)

[62] Measurement of the C-forbidden 2 ^{3}S$_1$ $\rightarrow$ 2 ^{1}P$_1$ transition in positronium (14:15)

Presenter: DALY, Rebecca J (University College London)

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 |□$2~^1 \mathrm{P}_1|H_{{C}{P}}|2~^3\mathrm{P}_1□|$.

[81] One-dimensional chirp cooling of positronium (14:40)

Presenter: Dr SHU, Kenji (The University of Tokyo)

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. [1] K. Shu *et al.*, arXiv:2310.08761 (2023). [2] K. Yamada *et al.*, Phys. Rev. Applied **16**, 014009 (2021). [3] K. Shu *et al.*, arXiv: 2308.00877 (2023).

[92] Laser Cooling of Positronium (15:05)

Presenter: RIENACKER, Benjamin (University of Liverpool (GB))

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 1^3S-3^3P 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. [1] L. T. Gloggler et al. (The AEgIS collaboration), Positronium Laser Cooling via the 13S−23P Transition with a Broadband Laser Pulse, Phys. Rev. Lett. 132 (2024), 083402, https://doi.org/10.1103/PhysRevLett.132.083402

Coffee break (15:30 - 16:00)

Session 8 (16:00 - 17:20)

[43] Progress in the calculation of order α^7 radiative-recoil corrections to the energy levels of muonium and positronium (16:00)

Presenter: ADKINS, Gregory

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.

[60] LEMING - Cold muonium for atomic physics and gravity (16:30)

Presenter: SOTER, Anna (ETH Zürich)

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 = μ□ + 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.

[58] Rydberg atom interferometry for testing the Weak Equivalence Principle with antimatter (16:55)

Presenter: MCCAUL, Louise

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. [1] P. Asenbaum, C. Overstreet, M. Kim, J. Curti, and M. A. Kasevich Phys. Rev. Lett. 125, 191101 (2020) [2] Anderson, E.K., Baker, C.J., Bertsche, W. et al., Nature 621, 716–722 (2023) [3] A. Deller, B. S. Cooper, S. D. Hogan and D. B. Cassidy, Phys. Rev. A 93, 062513 (2016) [4] Y. Margalit, O. Dobkowski, Z. Zhou, O. Amit, Y. Japha, S. Moukouri, D. Rohrlich, A. Mazumdar, S. Bose, C. Henkel, R. Folman, Sci. Adv 7, 22 (2021) [5] J. E. Palmer and S. D. Hogan, Phys. Rev. Lett 122, 250404 (2019); J. D. R. Tommey and S. D. Hogan, Phys. Rev. A 104, 033305 (2021)

Friday, 14 June 2024

Session 9 (09:00 - 10:15)

[11] Proton Structure in and out of muonic hydrogen (09:00)

Presenter: HAGELSTEIN, Franziska (JGU Mainz & PSI)

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. [1] A. Antognini, F. Hagelstein and V. Pascalutsa, Ann. Rev. Nucl. Part. Sci. 72 (2022) 389 [2] F. Hagelstein, V. Lensky, and V. Pascalutsa, Eur. Phys. J. C 83 (2023) 8, 762

[45] Nuclear contributions to two-photon exchange in muonic deuterium (09:25)

Presenter: LENSKY, Vadim (JGU Mainz)

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]. [1] K. Pachucki, V. Lensky, F. Hagelstein, S. Li Muli, S. Bacca, R. Pohl, Rev. Mod. Phys. **96** (2024), 015001 [arXiv:2212.13782 [physics.atom-ph]] [2] A. Antognini, F. Hagelstein and V. Pascalutsa, Ann. Rev. Nucl. Part. Sci. **72** (2022) 389 [arXiv:2205.10076 [nucl-th]] [3] V. Lensky, F. Hagelstein and V. Pascalutsa, Eur. Phys. J. A **58** (2022), 224 [arXiv:2206.14756 [nucl-th]]. [4] V. Lensky, F. Hagelstein and V. Pascalutsa, Phys. Lett. B **835** (2022), 137500 [arXiv:2206.14066 [nucl-th]].

[20] Searching for ultralight scalar dark matter with muonium and muonic atoms (09:50)

Presenter: Dr STADNIK, Yevgeny (The University of Sydney)

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. **References:** Y. V. Stadnik, PRL **131**, 011001 (2023). Y. V. Stadnik and V. V. Flambaum, PRL **114**, 161301 (2014); PRL **115**, 201301 (2015).

Coffee break (10:15 - 10:45)

Session 9 (10:45 - 12:30)

[51] Precision Measurements of Muonium and Muonic Helium Hyperfine Structure at J-PARC (10:45)

Presenter: Dr STRASSER, Patrick (KEK)

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. [1] M. I. Eides, Phys. Lett. B **795**, 113 (2019) [2] S. Kanda *et al.*, Phys. Lett. B **815**, 136154 (2021) [3] S. Nishimura *et al.*, Phys. Rev. A **104**, L020801 (2021) [4] P. Strasser *et al.*, Phys. Lett. **131**, 253003 (2023) [5] A. S. Barton *et al.*, Phys. Rev. Lett. **70**, 758 (1993)

[2] Towards improved charge radii from Lithium to Neon (11:15)

Presenter: Prof. OHAYON, Ben (Technion IIT)

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^{6}Li 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

[44] Status of the FAMU experiment (11:45)

Presenter: PIZZOLOTTO, Cecilia

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.

[70] The ground state hyperfine splitting in muonic hydrogen (Hyper-mu) experiment at PSI. (12:05)

Presenter: Mr OUF, Ahmed (johannes gutenberg universität mainz)

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.

Lunch break (Bellavista) (12:30 - 14:15)

Lab visits (14:15 - 16:00)