A 31: Precision Spectroscopy of Atoms and Ions VI (joint session A/Q)

Time: Thursday 14:30–16:30 Location: KlHS Mathe

Invited Talk A 31.1 Thu 14:30 KlHS Mathe

Characterization of an XUV Frequency Comb by Spectroscopy of Rydberg States — •Lennart Guth, Jan-Hendrik Oelmann, Tobias Heldt, Janko Nauta, Nick Lackmann, Anant Agarwal, Lukas Matt, Thomas Pfeifer, and José R. Crespo López-Urrutia — Max-Planck-Institut für Kernphysik, Heidelberg, Germany

We aim to use ultra-narrow transitions in highly charged ions (HCI) for novel frequency standards and fundamental physics studies. These transitions occur in the extreme ultraviolet (XUV), where narrow-bandwidth laser sources are unavailable. To address this, we built an XUV frequency comb that transfers coherence from a near-infrared (NIR) comb to the XUV via high harmonic generation (HHG) [1,2]. Using intra-cavity HHG, our system generates harmonics up to 40 eV with μW power in each order.

We propose resonance-enhanced two-photon spectroscopy as a preliminary test towards spectroscopy of HCI, aiming to resolve individual teeth of our XUV comb and characterize its properties. In this approach, we excite neutral argon with one photon from a referenced 13^{th} harmonic comb tooth to a Rydberg state, followed by ionization with a narrow-bandwidth continuous wave NIR laser. We then use velocity-map imaging to record the momentum of the released electrons, allowing us to identify the resonant Rydberg state.

[1]Opt. Express 29, Issue 2, pp. 2624-2636 (2021)
[2]Rev. Sci. Instrum. 95, 035115 (2024)

A 31.2 Thu 15:00 KlHS Mathe

Simulating coupled oscillators in a Penning trap for (anti-)proton g-factor measurements — •Nikita Poljakov[1], Jan Schaper[1], Julia Coenders[1], Yannick Priewich[1], Juan Manuel Cornejo[1], Stefan Ulmer[3,4], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Germany — [2]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [3]Ulmer Fundamental Symmetries Laboratory, RIKEN, Japan — [4]Heinrich-Heine-Universität Düsseldorf, Germany

The BASE collaboration tests CPT symmetry via high-precision measurements of the (anti-)proton charge-to-mass ratio [1] and g-factor [2]. To improve g-factor sampling rates, we are developing quantum logic spectroscopy [3] with a laser-cooled $^9Be^+$ ion in a cryogenic Penning trap. This requires cooling the $^9Be^+$ ion and (anti-)proton to their motional ground states. Key milestones include optical sideband spectroscopy [4], ground-state cooling of a single $^9Be^+$ ion [5], and fast adiabatic transport [6]. We aim to couple an (anti-)proton to a cooled $^9Be^+$ ion via Coulomb interaction in a double-well potential created by a microfabricated trap. Here, we present project updates and simulations of coupled $^9Be^+$ ions and a single $^9Be^+$ ion coupled to an (anti-)proton.

[1] M.J. Borchert et al., Nature 601 (2022) [2] C. Smorra et al., Nature 550 (2017) [3] P.O. Schmidt et al., Science 309 (2005) [4] J.M. Cornejo et al., Phys. Rev. Res. 5 (2023) [5] J.M. Cornejo et al., Phys. Rev. Res. 6 (2024) [6] T. Meiners et al., Eur. Phys. J. Plus 139 (2024)

A 31.3 Thu 15:15 KlHS Mathe

Probing parity violating interactions beyond the Standard Model with molecular spectroscpy — •Konstantin Gaul — Helmholtz Institute Mainz, Staudingerweg 18, 55128 Mainz

Dark spin-1 bosons, such as dark photons or Z' bosons, are particularly interesting dark matter (DM) candidates which are predicted by several theories that extend the Standard Model (SM). The Z' boson could act as a possible link between visible matter and DM and would be a source for a violation of parity beyond the SM [1]. Studying such parity violating interactions over a broad range of boson masses M is challenging for common low-energy dark matter detection methods [2]. In contrast, experiments based on internal interactions of atoms or molecules are sensitive to *long* range interactions $M \to \infty$, as well as interactions at much *shorter* range on the scale of atomic sizes $M \gtrsim 10^3\,\text{eV}/c^2$ and even down to nuclear sizes $M \gtrsim\sim 10^8\,\text{eV}/c^2$ and could, therefore, provide a versatile platform to study parity violating dark matter [2]. An abundance of close-lying states of opposite parity, which can enhance parity violating interactions by several orders of magnitude, renders polar linear molecules and chiral molecules particularly interesting for this purpose [3,4]. In this contribution the sensitivity of current molecular experiments to Z' bosons and prospects of future experiments will be discussed from a theory perspective.

[1] A. Alves et al., JHEP. 2014, 63 (2014).
[2] L. Cong et al, arXiv, hep-ph, 2408.15691 (2024).
[3] K. Gaul et al. PRL 125, 123004; PRA 102, 032816 (2020).
[4] Baruch et al., PRResearch 6, 043115 (2024).

A 31.4 Thu 15:30 KlHS Mathe

Accurate isotope shift measurements in the 5s→5p and 4d→5p lines of Sr+ — •Julian Palmes, Kristian König, Hendrik Bodnar, Patrick Müller, Imke Lopp, Julien Spahn, and Wilfried Nörtershäuser — Institut für Kernphysik, TU Darmstadt, Germany

Accurate measurements of different transition frequencies in multiple isotopes allow for the determination of the isotope shift and thus the calculation of the field-shift ratio F_i/F_j , which is an important parameter to compare experimental results with state-of-the-art atomic structure calculations. In 2016, Shi et al. [1] measured the F_{D2}/F_{D1} field shift ratio in Ca^+ to be above theoretical boundaries set by the hydrogenic model, which set off a series of measurements in Ca^+ [2], Ba^+ [3] and now Sr^+ at the Collinear Apparatus for Laser Spectroscopy and Applied Science (COALA) at the Technical University of Darmstadt. We report absolute frequency measurements of the stable Sr^+ isotopes of the $5s \to 5p$ and the $4d \to 5p$ transitions. A King plot analysis was performed to extract the field shift ratio F_{D2}/F_{D1}, and utilizing the $4d \to 5p$ transitions, ring closures were formed for self-consistency. Additionally, this method allowed for a precise observation of the hyperfine splitting of the $^{87}Sr^+$ isotope, which is the first step for the investigation of the magnetic octupole moments at the BICEPS trap.
Funding by BMBF under contract 05P21RDFN1 is acknowledged.

[1] Shi et al., Applied Physics B 123, 2 (2016)
[2] Müller et al., Physical Review Research 2.4 (2020)
[3] Imgram et al., Physical Review A 99.1 (2019)

A 31.5 Thu 15:45 KlHS Mathe

High resolution spectroscopy of Mossbauer materials using Ptychography — •Ankita Negi[1], Lars Bocklage[1], Leon Merten Lohse[1], Sven Velten[1], Guido Meier[2], Ralf Röhlsberger[3], and Christina Brandt[4] — [1]Deutsches Elektronen Synchrotron, Hamburg, Germany — [2]Max Planck Institute for the structure and dynamics of matter, Hamburg, Germany — [3]Friedrich Schiller Universität Jena, Jena, Germany — [4]Universität Greifswald, Greifswald, Germany

Mössbauer spectroscopy is a technique for measuring atomic-level magnetic and chemical properties of materials. The "Mössbauer effect" allows nuclei to absorb or emit gamma radiation without losing energy to the lattice. Advances in synchrotron sources have enabled measurements of nuclear resonant scattering (NRS) of synchrotron gamma-ray pulses, offering better sensitivity and faster data collection compared to spectroscopy with traditional radioactive sources. However, extracting spectral information from a single time-domain NRS measurement is challenging and requires extensive modeling. To address this, we modify the setup and use multiple overlapping NRS measurements to extract both the transmission spectrum and phase. Our approach, inspired by phase retrieval algorithms in ptychography, frames the problem as a one-dimensional phase retrieval. We demonstrate the robustness of our method with ^{57}**Fe**-enriched samples, showing that, unlike traditional Mössbauer spectroscopy, our technique overcomes bandwidth limitations of gamma-ray sources, offering new possibilities for research with modern X-ray sources and other Mössbauer isotopes.

A 31.6 Thu 16:00 KlHS Mathe

Improvement of the bound-electron g-factor theory after completion of two-loop QED calculations — •Bastian Sikora, Vladimir A. Yerokhin, Christoph H. Keitel, and Zoltán Harman — Max Planck Institute for Nuclear Physics, Heidelberg, Germany

The bound-electron g-factor in hydrogenlike ions can be measured and calculated with high precision. In a recent collaboration, the experimental and theoretical g-factors of the bound electron in hydrogenlike tin were found to be in excellent agreement [1]. However, the theoretical uncertainty is orders of magnitude larger than the experimental

uncertainty due to uncalculated QED binding corrections at the two-loop level.

In our new work, we report the completed calculation of QED Feynman diagrams with two self-energy loops contributing to the g-factor using the Furry picture approach, i.e. taking into account the electron-nucleus interaction exactly [2]. We demonstrate that our results allow a significant improvement of the total theoretical uncertainty of the bound-electron g-factor.

Our calculations will enable improved tests of QED in planned near-future experiments, e.g. at ALPHATRAP and ARTEMIS, and are relevant for the determination of fundamental constants as well as searches for physics beyond the standard model using heavy ions.

[1] J. Morgner, B. Tu, C. M. König, et al., Nature 622, 53 (2023)

[2] B. Sikora, V. A. Yerokhin, C. H. Keitel and Z. Harman, arXiv:2410.10421v1 [physics.atom-ph]

A 31.7 Thu 16:15 KlHS Mathe

Development of a non-collinear enhancement resonator for a VUV frequency comb nuclear clock laser — •Stephan H. Wissenberg[1,2,3], Johannes Weitenberg[1,4], Akira Ozawa[4], Tamila Teschler[2], Mahmood I. Hussain[3], Peter G. Thirolf[3], Hans-Dieter Hoffmann[1], and Constantin L. Haefner[1,2] — [1]Fraunhofer ILT, Aachen — [2]RWTH Aachen University, Aachen — [3]LMU, Munich — [4]MPQ, Garching

229-Thorium is unique in possessing a nuclear transition energy accessible by current laser technology, making it suitable for a nuclear clock's operation. To drive the nuclear transition, we are building a vacuum-ultraviolet (VUV) frequency comb at 148 nm, derived from a high-power infrared frequency comb via resonator-assisted high-harmonic generation (HHG). Our design features a non-collinear enhancement resonator where two intersecting circulating beams enable efficient geometric output-coupling of the VUV beam. Synchronizing and aligning these beams poses a challenge. We describe a resonator design employing wedge mirrors which avoids the need for separate mirrors for the two circulating beams, providing intrinsic synchronization and alignment. We provide detailed characterization measurements using a cw-laser to showcase the versatility of this non-collinear resonator design. Furthermore, cylindrical mirrors are incorporated to modify the focus's ellipticity, reducing cumulative plasma effects. Achieved ellipticities of $\epsilon > 3$ do not compromise the resonator's enhancement factor of >50. Work supported by the ERC Synergy Grant 'ThoriumNuclearClock' (Grant 856415).