A 4: Precision Spectroscopy of Atoms and Ions II (joint session A/Q)

Time: Monday 17:00–19:00 Location: HS PC

Invited Talk A 4.1 Mon 17:00 HS PC

Precision Measurements to Test Theory at ALPHATRAP — •Matthew Bohman[1], Fabian Heisse[1], Charlotte König[1], Ivan Kortunov[2], Jonathan Morgner[1], Victor Vogt[2], Klaus Blaum[1], Stephan Schiller[2], and Sven Sturm[1] — [1]Max-Planck-Institut für Kernphysik, 69117 Heidelberg — [2]Institute für Experimentalphysik, Univ. Düsseldorf, 40225, Düsseldorf

ALPHATRAP [1] is a Penning-trap apparatus located at MPIK in Heidelberg used to perform high-precision measurements of simple atomic systems. In few-electron highly charged ions, the bound electron g-factor is a highly sensitive probe of new physics and its measurement allows us to test quantum electrodynamics (QED) at extremely high fields with sub-ppb accuracy, which we have recently done with H-like, Li-like, and B-like tin [2]. However, Penning trap g-factor experiments also provide unique opportunities to perform experiments on simple molecular ions such as HD$^+$ and H$_2^+$. We have recently developed techniques to track the hyperfine and ro-vibrational state of a single HD$^+$ ion in the presence of external perturbations, and were able to prepare the ion in the ro-vibrational ground state and measure the hyperfine structure and bound electron g-factor to high precision [3], laying the foundation for upcoming high-precision laser spectroscopy of HD$^+$ that will allow us to test QED and extract fundamental constants.

[1] Sturm, S. et al. Eur. Phys. J. Spec. Top. 227, 14251491 (2019).
[2] Morgner, J., Tu, B., König, C. et al. Nature 622, 5357 (2023).
[3] C. König, F. Heiße, J. Morgner, *et al.* In preparation.

A 4.2 Mon 17:30 HS PC

The Cryogenic Ion Trap Experiment for Laser Excitation of ^{229}Th^{3+} at LMU — •Markus Wiesinger, Kevin Scharl, Georg Holthoff, Tamila Teschler, Mahmood I. Hussain, and Peter G. Thirolf — Ludwig-Maximilians-Universität München

The isomeric first excited state in ^{229}Th with an excitation energy of only about 8.356 eV provides a unique opportunity for the development of an optical clock based on a nuclear transition – a nuclear clock. Attractive properties such as insensitivity to environmental conditions and long lifetime promise to enable new applications in fundamental physics, precision metrology, and geodesy.

At LMU work is ongoing towards the realization of a lifetime measurement of the isomeric state, and VUV spectroscopy of the nuclear transition in trapped ^{229}Th^{3+} ions. To this end, a cryogenic ion trap has been set up and commissioned. As a prerequisite, nuclear state readout based on optical hyperfine spectroscopy of trapped Th^{3+} ions is currently being prepared.

In this talk we will focus on the experimental setup of the cryogenic ion trap: We will discuss our ion sources and ion loading procedures. We will show sympathetic laser cooling of ^{229}Th^{3+} by Doppler-cooled ^{88}Sr$^+$ ions and the formation of mixed-species Coulomb crystals. The use of a radioactive ^{233}U source will allow to conduct experiments not only with ^{229}Th in the ground state, but also in the isomeric excited state (populated in 2% of the decays) – enabling a lifetime measurement without preceding laser excitation of the nuclear transition.

We acknowledge support by ERC (856415) and BaCaTec (7-2019-2).

A 4.3 Mon 17:45 HS PC

Quantum Logic Control of Complex Systems — •Till Rehmert[1,2], Maximilian J. Zawierucha[1,2], Kai Dietze[1,2], Piet O. Schmidt[1,2], and Fabian Wolf[1] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig — [2]Leibniz Universität Hannover

Extending quantum control to increasingly complex systems is crucial for advancing quantum technologies and fundamental physics. Molecules, for instance, offer a rich level structure, permanent dipole moments, and large internal electric fields, making them exceptionally suitable for quantum applications. However, their additional degrees of freedom necessitate sophisticated techniques for cooling, optical pumping, and precise state detection. In trapped ion systems, quantum logic techniques that combine a well-controlled logic ion species with a more complex spectroscopy ion have emerged as powerful tools to overcome these challenges. Using a calcium ion as the logic ion and a co-trapped titanium ion, we have developed schemes for state detection and coherent manipulation of the spectroscopy ion through a far-detuned Raman laser setup. Our results demonstrate the coherent control of different Zeeman manifolds within the a^{4}F ground state of the titanium ion and include precise measurements of the corresponding Landé g-factors. The universal applicability of the Raman laser approach facilitates the transfer of these methods to other qudit systems, such as molecules, all aiming for high-precision spectroscopy. By enhancing the control in these systems, our work paves the way for novel applications in quantum technology and fundamental physics research by making an entire new class of ions accessible to spectroscopy.

A 4.4 Mon 18:00 HS PC

Neural-network approach to large atomic structure computations with pCI and other atomic codes — •Pavlo Bilous[1], Charles Cheung[2], and Marianna Safronova[2] — [1]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany — [2]Department of Physics and Astronomy, University of Delaware, Delaware 19716, USA

Atomic structure computations deliver information on atomic properties crucial for applications including atomic frequency standards and analysis of astrophysical spectra. The increasing precision demands lead often to prohibitively large sets of electronic configurations which need to be included in the configuration interaction (CI) framework for accurate modeling of electronic correlations. This necessitates development of efficient configuration selection methods, as well as their integration with existing high-performance atomic codes.

We present a neural-network (NN) approach for efficient selection of electronic configurations integrated with the established pCI atomic codes [1]. The method is applied to otherwise prohibitively large CI computations for the Fe^{16+} and Ni^{12+} energy levels and verified within a few cm^{-1} with an alternative approach of basis upscaling without NN. Our implementation of the NN-supported algorithm allows for integration with other atomic codes providing an efficient and novel tool for a broader atomic physics community.

[1] P. Bilous, C. Cheung, and M. Safronova, Phys. Rev. A 110, 042818 (2024).

A 4.5 Mon 18:15 HS PC

Hyper-EBIT: The development of a source for very highly charged ions — •Luca Yannik Geissler, Matthew Bohman, Athulya Kulangara Thottungal George, Fabian Heisse, Charlotte Maria König, Jonathan Morgner, José Ramon Crespo López-Urrutia, Klaus Blaum, and Sven Sturm — Max-Planck-Institut für Kernphysik, 69117 Heidelberg

Quantum electrodynamics (QED) is considered to be the most successful quantum field theory in the Standard Model. Its most precise test is conducted via the comparison of QED calculations with the measurement of the free electron g-factor. However, this test is restricted to low electrical field strengths. Consequently, it is of utmost importance to perform similar tests at high field strengths.

Such tests can be performed using highly charged ions (HCI). Here, only a few or even a single one of the innermost electrons are left, experiencing the strong field originating from the nucleus. The ALPHATRAP experiment is a cryogenic Penning-trap experiment, which is dedicated to perform precision measurements of the HCI's bound-electron magnetic moments.

Recently, we have measured the bound-electron g factor of hydrogen-like tin with ALPHATRAP to sub parts-per-billion precision. Our goal is to further advance such tests towards the heaviest HCIs such as ^{208}Pb^{81+}. For the production of ^{208}Pb^{81+} an electron beam ion trap, Hyper-EBIT, is being constructed at the MPIK with planned beam energies of 300 keV and up to 500 mA beam currents. This contribution presents the recent developments of the Hyper-EBIT.

A 4.6 Mon 18:30 HS PC

Laser spectroscopy of the hyperfine structure of sympathetically cooled ^{229}Th^{3+} ions — •Gregor Zitzer, Johannes Tiedau, Maksim Okhapkin, and Ekkehard Peik — Physikalisch-Technische Bundesanstalt, Braunschweig

The isotope ^{229}Th has a low-lying isomeric state at only about 8.4 eV which enables resonant laser excitation. Future versions of optical clocks are planned to use this special property. For an improved understanding of the nuclear structural changes underlying the low-energy transition, knowledge of the nuclear moments of the ground and isomeric state is required. The hyperfine structure of ^{229}Th^{3+} ions in the nuclear ground state are investigated via laser spectroscopy on ^{88}Sr^{+} sympathetically cooled ions confined in a linear Paul trap. The relative isotope shift to ^{230}Th^{3+} and the hyperfine constants for the magnetic dipole (A) and electric quadrupole (B) for the 5F$_{5/2}$ and 6D$_{5/2}$ electronic states are determined. The new values reduce the uncertainties of previous measurements.

A 4.7 Mon 18:45 HS PC

Fiber-Based Phase Noise Cancellation for Links in Networks of Optical Clocks — •Jonas Kankel[1,2], Luis Hellmich[1,2], Steven Worm[1,2], Ullrich Schwanke[2], Lakshmi Kozhiparambil[1,3], Yang Yang[1,3], and Cigdem Issever[1,2] — [1]DESY (Deutsches Elektronen-Synchrotron), Zeuthen, Germany — [2]Platanenallee 6 — [3]Max-Planck-Institut für Kernphysik Heidelberg, Germany

Modern optical atomic clocks, with fractional uncertainties on the order of 10^{-19}, enable the exploration of fundamental physics, such as the temporal variation of fundamental constants and constraints on dark matter models. The fine-structure constant α, predicted to vary in many theories of new physics, can be probed using atomic clocks due to the sensitivity of clock transitions to changes in α.

We aim to build a highly-charged ion (HCI) clock in order to set new limits on variations of α and translate these measurements into bounds on ultra-light scalar dark matter models. Initially, we will compare our HCI clock to a local Sr-lattice clock. In anticipation of comparing clocks not only across one institute but in national or international networks, long-distance transmission of ultra-stable frequency references is required, typically through fiber optic cables. Reference signals are degraded by phase noise from environmental factors like temperature fluctuations and vibrations. We are investigating a fiber-based variant of a Michelson interferometer for active phase noise cancellation in a phase-locked loop scheme.