Q 20: Atom & Ion Clocks and Metrology I

Time: Tuesday 11:00–12:45 Location: HS Botanik

Invited Talk Q 20.1 Tue 11:00 HS Botanik

Towards quantum logic inspired techniques for high-precision measurements in Penning traps — •Juan Manuel Cornejo[1], Jan Schaper[1], Nikita Poljakov[1], Julia-Aileen Coenders[1], Stefan Ulmer[2,3], and Christian Ospelkaus[1,4] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Germany — [2]Ulmer Fundamental Symmetries Laboratory, RIKEN, Japan — [3]Heinrich-Heine-Universität Düsseldorf, Germany — [4]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

High-precision experiments in Penning traps have provided the most stringent tests of CPT invariance in the baryonic sector through (anti-)proton q/m ratio and g-factor measurements [1,2]. Within the BASE collaboration [3], we aim to develop quantum logic cooling and detection techniques to enable full motional control over single ions, reducing systematic errors and overall measuring time in (anti-)proton g-factor experiments [4]. In this contribution, we discuss the experimental procedure for implementing these techniques employing a single laser-cooled $^9Be^+$ ion as both a "cooling" and "detection" ion. Furthermore, our recent findings on the manipulation of single $^9Be^+$ ions in our cryogenic multi-Penning trap stack will be presented.

[1] C. Smorra *et. al.*, Nature **550**, 371-374 (2017).
[2] M. J. Borchert *et. al.*, Nature **601**, 53-57 (2022).
[3] C. Smorra *et. al.*, Eur. Phys. J. Special Topics **224**, 3055 (2015).
[4] J. M. Cornejo *et. al.*, New J. Phys. **23**, 073045 (2021).

Q 20.2 Tue 11:30 HS Botanik

Exploring the hyperfine structure of the $D_{5/2}$ state of ^{173}Yb$^+$ — •Ikbal Biswas[1], Jialiang Yu[1], Anand Prakash[1], Elena Jordan[1], and Tanja Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany — [2]Leibniz Universität Hannover, Hannover, Germany

The ytterbium ion (Yb$^+$) is highly interesting for precision spectroscopy, as it has three clock transitions: two electric quadrupole (E2) and an electric octupole (E3) transition. In addition, it has some unique properties like high sensitivity to the variation of the fine structure constant, high angular momentum of the $F_{7/2}$ state with a lifetime of 1.6 years, which makes Yb$^+$ an ideal candidate for tests of fundamental physics such as the test of local Lorentz invariance, the search for the new Boson, etc.

In order to improve the stability of clock operation with multiple ions, it is challenging to simultaneously excite the ions in a Coulomb crystal on a transition with the strong AC Stark shift. In that sense, compared to the other isotopes, ^{173}Yb$^+$ is an interesting candidate for multi-ion clock operation and tests of fundamental physics due to the predicted hyperfine quenching (and thus a reduced AC Stark shift). Due to its large nuclear spin, precision spectroscopy of this new isotope gives insight of nuclear spin interaction. Both the energy levels and the hyperfine structure of ^{173}Yb$^+$ have not yet been explored. In this work, we present the first measurement of the hyperfine structure of the $D_{5/2}$ clock state and the coefficient of the hyperfine interaction by interrogating the E2 transition at 411 nm.

Q 20.3 Tue 11:45 HS Botanik

Clock comparisons with an aluminium ion clock at the 10^{-17} level — •Fabian Dawel[1,2], Derwell Drapier[1], Lennart Pelzer[1], Vincent Barbé[1], Kai Dietze[1,2], Marek Hild[1,2], Johannes Kramer[1,2], and Piet O. Schmidt[1,2] — [1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [2]Leibniz Universität Hannover, 30167 Hannover, Germany

The SI second is defined by a hyperfine transition in caesium. Currently it is discussed to redefine the second using optical frequency standards with lower statistical and systematic uncertainty. One criterion for the redefinition is the agreement of measured frequency ratios from different institutes at a level of $< 5 \times 10^{-18}$, to validate the frequency uncertainty budgets. Here, we present frequency ratio measurements of an aluminium ion clock. For the measurement we use a Ramsey interrogation time of 300 ms, while simultaneous sympathetically cooling via a co-trapped calcium ion. Electromagnetic transparency (EIT) cooling cools all six motional modes close to the motional ground state and keeps the time dilation shift independent from the probe time. Using EIT cooling during interrogation induces a light shift on the clock transition. With calcium as a sensor, we can measure the electric field of the cooling lasers and evaluate the systematic frequency uncertainty of the aluminium ion. We compared our clock against a ^{87}Sr lattice clock and a ^{171}Yb$^+$ ion clock and measure the ratios.

Q 20.4 Tue 12:00 HS Botanik

Integrated Photonic AlN-Based High-Bandwidth Phase Modulator for Precision Control in Yb+ Ion Experiments — •Suat Icli[1,2], Rangana Banerjee Chaudhuri[1], Elena Jordan[1], Fatemeh Salahshoori[1], and Tanja E. Mehlstäubler[1,2,3] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — [3]Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover, Hannover, Germany

This work introduces an aluminum nitride (AlN)-based phase modulator designed for precision control in ytterbium ion trapping experiments, which require modulation across a range of wavelengths from UV to IR and frequencies from hundreds of MHz to GHz. Such devices are critical in atomic physics for achieving fine control over laser frequency and phase, directly impacting ion cooling and state preparation. The photonic AlN phase modulator achieves an electrical bandwidth from low frequencies up to 40 GHz, with low S21 (-2 dB) and S11 (-18 dB) ensuring efficient modulation over the bandwidth. At a wavelength of e.g. 411 nm the voltage-length product of 178 V.cm leads to a modulation index of 0.018*U where U is applied voltage. This highlights the suitability of the AlN platform for efficient integrated modulators. The platform offers scalable photonic components for atomic physics, establishing a versatile foundation for next-generation quantum research and technology development.

Q 20.5 Tue 12:15 HS Botanik

Recent advances of PTB's transportable Al$^+$ ion clock — •Constantin Nauk[1,2], Joost Hinrichs[1,2], Gayatri Sasidharan[1,2], Vanessa Galbierz[1], Benjamin Kraus[1], Sofia Herbers[1], and Piet O. Schmidt[1,2] — [1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [2]Leibniz Universität Hannover, Institut für Quantenoptik, 30167 Hannover, Germany

Optical atomic clocks demonstrate exceptional fractional systematic and statistical frequency uncertainties on the order of 10^{-18}, opening the door to novel applications. In particular, transportable clocks enable applications in relativistic geodesy, e.g. height measurements at the cm level or dynamic Earth monitoring, which require highly robust and reliable hardware.

We present a transportable clock setup based on the $^1S_0 \rightarrow {}^3P_0$ transition in ^{27}Al$^+$, utilizing a co-trapped ^{40}Ca$^+$ ion to enable state detection and cooling through quantum logic spectroscopy and sympathetic cooling. The physics package is fully integrated in commercial 19" racks and comprises an ion trap in an aluminum/titanium composite vacuum system. We detail the optimization of ion loading efficiency, Doppler cooling, and micromotion compensation. Additionally, we show characterization measurements, including trap temperatures, secular motion, and ion swap rates. Finally, we demonstrate coherent manipulation on the $S_{1/2} \rightarrow D_{5/2}$ transition in ^{40}Ca$^+$, required for quantum logic spectroscopy.

Q 20.6 Tue 12:30 HS Botanik

Photon recoil spectroscopy enhanced by squeezing and statistical tests. — •Ivan Vybornyi and Klemens Hammerer — Institut für theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany

In photon recoil spectroscopy, internal transitions of atoms or molecules are identified from the recoil and the resulting motional displacement caused by an applied light field of variable frequency. A notable example of this "needle in a haystack" problem is the search for narrow clock transitions in highly charged ions, as recently discussed in [Phys. Rev. Applied 22, 054059]. A key challenge is to increase the scan speed over a frequency bandwidth by enhancing the sensitivity of displacement detection. In this work, we explore two complementary improvements: the use of squeezed motional states and optimal statistical postprocessing of data within a hypothesis testing framework. We demonstrate that each method independently provides a substantial boost to scan speed, while their combination effectively mitigates state preparation and measurement errors, fully leveraging the quantum enhancement offered by squeezing.