Q 32: Atom & Ion Clocks and Metrology II

Time: Wednesday 11:00–13:00 Location: HS Botanik

Invited Talk Q 32.1 Wed 11:00 HS Botanik

Exploring fundamental constants with high-precision spectroscopy of molecular hydrogen ions — •Soroosh Alighanbari, Magnus R. Schenkel, and Stephan Schiller — Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany

Molecular hydrogen ions (MHIs) have great potential for refining our understanding of fundamental physics, e.g. novel tests of CPT invariance and determination of fundamental constants (FCs). Among the MHI isotopologues, HD^+ has been intensely studied, providing precise data on transitions frequencies, in agreement with ab initio predictions [1]. Homonuclear H_2^+ presents challenges for laser spectroscopy due to the absence of electric-dipole transitions. We succeeded in the measurement of an electric-quadrupole transition in H_2^+, overcoming historical limitations [2]. We have also performed a Doppler-free spectroscopy of H_2^+ and have measured a first-overtone transition. We have determined the spin-averaged transition frequency, enabling the derivation of a value of m_p/m_e. The value is consistent with the recent CODATA2022 value [3] and the uncertainty is comparable. This work marks a significant step toward refining FCs and presents progress towards a test of CPT invariance through comparison of a single transition in H_2^+ and anti-H_2^+. Precision spectroscopy of a set of transitions in all MHI isotopologues enables the determination of FCs, including nuclear radii, with improved uncertainties. [1] S. Schiller, Cont. Phys. 63, 247 (2022). [2] M.R. Schenkel, et al. Nat. Phys. 20, 383 (2023). [3] S. Alighanbari, et al. Under review in Nature (2024).

Q 32.2 Wed 11:30 HS Botanik

Ramsey-Bordé atom interferometry with a thermal strontium beam for a compact optical clock — •Oliver Fartmann[1], Marc Christ[2], Amir Mahdian[1], Vladimir Schkolnik[1], Ingmari C. Tietje[1], Levi Wihan[1], and Markus Krutzik[1,2] — [1]Humboldt-Universität, Inst. f. Physik, Newtonstr. 15, 12489 Berlin — [2]Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Straße 4, 12489 Berlin

Compact optical atomic clocks have become increasingly important in field applications and clock networks. Systems based on Ramsey-Bordé interferometry (RBI) with a thermal atomic beam offer higher stability than optical vapour cell clocks while being less complex than cold atom clocks.

Here, we demonstrate RBI with strontium atoms, utilizing the narrow $^1S_0 \rightarrow {}^3P_1$ intercombination line at 689 nm, yielding a 60 kHz broad spectral feature [1].

The obtained Ramsey fringes for varying laser power are analyzed and compared with a numerical model. The atomic state is detected via fluorescence either on the $^1S_0 \rightarrow {}^1P_1$ transition at 461 nm or on the $^3P_1 \rightarrow {}^3P_0$ transition at 483 nm, limited by atomic shotnoise.

We present the experimental setup, our clock stability measurements and our progress towards more compact systems for mobile and space applications.

[1] Fartmann et al. "Ramsey-Borde Atom Interferometry with a Thermal Strontium Beam for a Compact Optical Clock." arXiv preprint arXiv:2409.05581 (2024).

Q 32.3 Wed 11:45 HS Botanik

High precision test of the equivalence of active, passive, and gravitating mass — •Claus Lämmerzahl and Eva Hackmann — ZARM, University of Bremen, Germany

The kilogram is one of the basic physical units. It has been given by the Paris prototype consisting of platinum and Iridium. Recently, within the new SI (Systeme International) the kilogram has been defined through the setting of the Planck constant.

While the Plack constant is unique, the operational definition of mass has a variety of aspects which need not be equivalent: We can define an *inertial* mass appearing on the "right" hand side of Newton's third axiom through, e.g, scattering processes, we have a *passive gravitational* mass which is the weight of a body in an external gravitational field, and we have the active gravitational or *gravitating* mass which creates a gravitational field. These three definitions are independent and in principle may lead to completely different quantities. However, high precision tests prove that these three masses are equivalent to very high precision.

Here we report on the basics notions, describe theoretical and metrological aspects as well as experimental implications of a hypothetical non-equivalence of these masses, and highlight the recent experimental progress on testing the equivalence of these masses achieved with Lunar Laser Ranging and with the MICROSCPE space mission, and outline future planned tests.

Q 32.4 Wed 12:00 HS Botanik

Towards Miniaturized Spaceborne Rubidium Two-Photon Frequency References — •Daniel Emanuel Kohl[1,2], Julien Kluge[1,2], Moritz Eisebitt[1,2], Janice Wollenberg[1], Klaus Döringshoff[1,2], and Markus Krutzik[1,2] — [1]Institut für Physik - Humboldt-Universität zu Berlin — [2]Ferdinand-Braun-Institut (FBH)

We present the development of a miniaturized rubidium two-photon frequency reference using the $5S_{1/2} \rightarrow 5D_{5/2}$ transition at 778.1 nm, in the context of the CRONOS project. The goal of the project is to demonstrate an optical clock on a micro-satellite in low earth orbit. Recent development of miniaturized two-photon references based on atomic vapor spectroscopy allow for the realization of compact clocks for application in next generation global navigation satellite systems.

We report on beat-note measurements between two laboratory-based references showing a fractional frequency instability below $1.7 \cdot 10^{-13}/\sqrt{\tau}$, reaching $6 \cdot 10^{-15}$ for an averaging time τ of 1000 s. We further present a prototype of a compact spectroscopy module achieving instabilities in the regime of $10^{-13}/\sqrt{\tau}$. The design comprises a volume below 0.5 l, mass below 1 kg and power consumption below 10 W. We show preliminary results of a frequency reference utilizing MEMS rubidium vapor cells, as a step towards chip-scale devices.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant numbers 50RK1971, 50WM2164.

Q 32.5 Wed 12:15 HS Botanik

Ultracold mercury as a probe for physics beyond the standard model — •Sascha Heider, Thorsten Groh, and Simon Stellmer — Physikalisches Institut, Universität Bonn, Nußallee 12, 53115 Bonn, Germany

Mercury, being one of the heaviest laser-coolable elements, is an ideal platform for beyond standard model physics like baryon asymmetry searches and isotope shift spectroscopy by exploring its relativistic nucleus and the large number of naturally occurring isotopes, all of which we laser cool in our lab.

We report on recent improvements and upgrades to the machine for transferring magneto-optically trapped mercury atoms to a high power optical dipole trap as a step towards degenerate quantum gases of mercury and measurements of the atomic electric dipole moment.

Q 32.6 Wed 12:30 HS Botanik

Entanglement dynamics of photon pairs and quantum memories in the gravitational field of the earth — Roy Barzel[1], Mustafa Gündoğan[2], Markus Krutzik[2], •Dennis Rätzel[1], and Claus Lämmerzahl[1] — [1]ZARM, University of Bremen, Am Fallturm 2, 28359 Bremen, Germany — [2]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin, Germany

We investigate the effect of entanglement dynamics due to gravity, the basis of a mechanism of universal decoherence, for photonic states and quantum memories in Mach-Zehnder and Hong-Ou-Mandel interferometry setups in the gravitational field of the earth. We show that chances are good to witness the effect with near-future technology in Hong-Ou-Mandel interferometry. This would represent an experimental test of theoretical modeling combining a multi-particle effect predicted by the quantum theory of light and an effect predicted by general relativity. Our article represents the first analysis of relativistic gravitational effects on space-based quantum memories which are expected to be an important ingredient for global quantum communication networks.

Q 32.7 Wed 12:45 HS Botanik

Scenario Building of a Quantum Space Gravimetry Mission for Earth Observation — •Gina Kleinsteinberg, Christian Struckmann, and Naceur Gaaloul — Leibniz University Hannover, Institute of Quantum Optics, Welfengarten 1, 30167 Hannover

Space-borne quantum sensors, being drift- and calibration-free, are in the future promising to outperform classical accelerometers currently used for space gravimetry. In the presence of climate change, quantum space gravimetry holds the potential to enable deeper insights into the changes in Earth's static and time-variable gravitational field, driven by the redistribution of large water masses.

To derive the precise requirements on the satellite platform and the experimental setup for a mission embarking a space-borne quantum sensor, extensive simulations are required. In this contribution, we present a simulation tool capable of building and analysing scenarios for quantum pathfinder gravimetry missions. This includes simulations of the atom interferometer itself as well as detailed analyses of systematic effects arising from environmental influences. To this end, multi-objective optimisation is used to explore options for balancing the multitude of mission parameters, while simultaneously optimising the sensor performance. The tool is developed in close cooperation with the geodesy community, leveraging the capabilities of classical satellite simulations and enabling the generation of realistic, synthetic atom interferometer phase signals. This work is supported by DLR funds from the BMWK (50WM2263A-CARIOQA-GE and 50WM2253A-(AI)^2).