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Clocks based on highly charged ions for tests of fundamental physics

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Highly charged ions (HCI) have many favorable properties. They offer a high sensitivity to test fundamental physics and for the search of new physics, a simplified atomic structure due to a small number of bound electrons, and a low susceptibility to external perturbing fields [1]. Therefore, HCI are also well-suited for next-generation optical atomic clocks, which can in principle operate at record fractional uncertainties of better than 10-18. However, up to recently HCI were not accessible for such type of instruments.
In this talk, I will briefly review how we overcame all previous obstacles by demonstrating Coulomb crystallization of HCI [2], the implementation of quantum logic spectroscopy [3], and ground-state cooling of weakly-coupled motional modes [4]. With these prerequisites we realized the first optical atomic clock based on an HCI by stabilizing an ultrastable clock laser to the ground-state fine-structure transition in Ar13+ at 441 nm. By comparing this optical frequency to the one of the electric-octupole transition in 171Yb+, we realized a frequency ratio measurement with a fractional uncertainty of about 1x10-16, limited by statistics. We thereby improved the uncertainty of the absolute transition frequency of Ar13+ by about eight orders of magnitude. The systematic uncertainty was 2.2x10-17, dominated by the time dilation shift uncertainty from excess micromotion. Importantly, this level of excess micromotion can be considerably reduced with a new, carefully manufactured ion trap. All other systematic uncertainties are at or below 10-18, demonstrating the potential of HCI as highly accurate atomic references for time keeping and unprecedented tests of fundamental physics. Furthermore, we compared the transition frequencies of the two isotopes 40Ar13+ and 36Ar13+ in order to determine the isotope shift with an improvement of nine orders of magnitude – resolving the QED nuclear recoil contribution.
The experimental approach is universal and thereby generally unlocks HCI for such precision experiments.

[1] M. G. Kozlov et al., Rev. Mod. Phys. 90 (2018)
[2] L. Schmöger et al., Science 347 (2015)
[3] P. Micke et al., Nature 578 (2020)
[4] S. A. King et al., Phys. Rev. X 11 (2021)

Primary authors: MICKE, Peter (CERN and University of Mainz); Dr KING, S. A. (Physikalisch-Technische Bundesanstalt); SPIEß, L. J. (Physikalisch-Technische Bundesanstalt); WILZEWSKI, A. (Physikalisch-Technische Bundesanstalt); Dr LEOPOLD, T. (Physikalisch-Technische Bundesanstalt); Dr BENKLER, E. (Physikalisch-Technische Bundesanstalt); Dr LANGE, R. (Physikalisch-Technische Bundesanstalt); Dr HUNTEMANN, N. (Physikalisch-Technische Bundesanstalt); Prof. SURZHYKOV, A. (Physikalisch-Technische Bundesanstalt and Technische Universität Braunschweig); Dr YEROKHIN, V. A. (Physikalisch-Technische Bundesanstalt); Prof. CRESPO LÓPEZ-URRUTIA, J. R. (Max Planck Institute for Nuclear Physics); Prof. SCHMIDT, P. O. (Physikalisch-Technische Bundesanstalt)

Presenter: MICKE, Peter (CERN and University of Mainz)

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