Optical Clocks Based on Highly Charged Ions

P. Micke[a,b], E. Benkler[a], S. Chen[b], E. A. Dijck[b], S. A. King[a], S. Kühn[b], T. Leopold[a], J. Nauta[b], J.-H. Oelmann[b], T. Pfeifer[b], N. Rehbehn[b], M. K. Rosner[b], L. Schmöger[b], L. J. Spieß[a], J. Stark[b], C. Warnecke[b], A. Wilzewski[a], J. R. Crespo López-Urrutia[b], P. O. Schmidt[a,c]

[a] *Physikalisch-Technische Bundesanstalt, Braunschweig*
[b] *Max-Planck-Institut für Kernphysik, Heidelberg*
[c] *Institut für Quantenoptik, Leibniz Universität Hannover*

Highly charged ions (HCI) offer excellent properties for novel high-accuracy atomic clocks. They not only have the potential to match or even exceed the accuracy level of world's leading optical clocks, but also offer record sensitivities to test our understanding of nature [1].

After demonstrating Coulomb crystallization [2], we recently accomplished the first coherent laser spectroscopy of a HCI as a successful proof of concept for such an optical clock [3]. In this work, we isolated a single Ar^{13+} ion from a hot plasma at a million kelvins and confined it together with a Be^{+} ion in a cryogenic Paul trap. This two-ion crystal was then cooled to its quantum-mechanical ground state of motion. Using quantum logic spectroscopy [4] and an ultrastable clock laser, we resolved the electric-dipole forbidden fine-structure transition of Ar^{13+} at 441 nm with a fractional frequency uncertainty of 3×10^{-15}. This is an improvement by eight orders of magnitude over the previous standard technique using a grating spectrometer. Furthermore, we measured the excited-state lifetime and g-factor. Since our experimental approach is universal, our work basically unlocks the entire atomic class of HCI for applications in frequency metrology and quantum information processing.

At PTB in Braunschweig we are currently preparing clock operation with Ar^{13+} for an absolute frequency measurement with a projected fractional statistical uncertainty in the 10^{-16} range, limited by the natural linewidth of the clock transition. In parallel, we develop methods to measure and control residual motional shifts at a fractional uncertainty level below 10^{-16}. We expect such shifts to ultimately limit an optical clock based on a HCI that offers a sufficiently narrow clock transition.

In Heidelberg at MPIK we recently commissioned a unique combination of superconducting radio-frequency cavity and linear Paul trap with a quality factor of 2.3×10^5 at 4.1 K [5]. We expect this apparatus to significantly suppress heating rates and motional shifts. Furthermore, we have developed an extreme ultraviolet (XUV) frequency comb using high-harmonic generation up to the 35^{th} order (42 eV or 30 nm) [6]. Combining both setups will allow XUV frequency metrology of HCI with the potential to boost the stability of an HCI clock. Additionally, we are exploring calcium HCI for their use in hertz-level isotope-shift spectroscopy to search for an unknown 5^{th} force between neutrons and electrons [7].

[1] M. G. Kozlov *et al.*, Rev. Mod. Phys. **90** (2018) 045005.
[2] L. Schmöger *et al.*, Science **347** (2015) 1233–1236.
[3] P. Micke, T. Leopold, S. A. King *et al.*, Nature **578** (2020) 60–65.
[4] P. Schmidt *et al.*, Science **309** (2005) 749–752.
[5] J. Stark *et al.*, arXiv:2102.02793 [physics.atom-ph] (2021).
[6] J. Nauta, *et al.*, Opt. Express **29** (2021) 2624–2636.
[7] N.-H. Rehbehn *et al.*, arXiv:2102.02309 [physics.atom-ph] (2021).