Systematic uncertainty evaluation and future improvements of an In^+ / Yb^+ Coulomb crystal clock

Ingrid M. Richter[1], H. Nimrod Hausser[1], Jonas Keller[1], Tabea Nordmann[1],

Tanja E. Mehlstäubler[1,2]

[1])Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2])Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Email: ingrid.richter@ptb.de

Optical clocks based on trapped ions are among the most accurate devices in metrology and can serve for tests of fundamental physics, as frequency standards or for applications such as relativistic geodesy [1,2]. Systematic uncertainties below 10^{-18} have been achieved [3] and are projected for a range of species in the coming years. Resolving frequencies at this level within feasible averaging times requires statistical uncertainties below $10^{-15}/\sqrt{\tau/1s}$. Our approach consists of small ensembles of clock ions in precision-machined ion trap arrays, which allow for 10^{-19} level systematic uncertainties [4].

We use $^{115}In^+$ as the clock species, co-trapped with $^{172}Yb^+$ for sympathetic cooling and shift characterization. The ions are stored in linear ion Coulomb crystals, whose permutation is actively controlled and has been chosen for efficient sympathetic cooling [5]. For operation with a 1 In^+-3 Yb^+ we report a detailed analysis of frequency shifts, yielding a finalized systematic uncertainty of 2.5×10^{-18} [6].

We present details on two planned measures for reducing systematic uncertainties:

By introducing a cooling stage using the $^1S_0 \leftrightarrow {}^1P_0$ line of the In^+ clock ions at 230 nm, we expect to reduce temperatures from close to Doppler temperature (~ mK, sympathetic cooling only) to below 100 µK, corresponding to a time dilation reduction from $1.7(16)\times10^{-19}$ to below 2×10^{-19}, thereby addressing the largest contribution in the current evaluation. Evaluating the resulting uncertainty will require an understanding of the cooling dynamics with a transition linewidth on the order of the crystal eigenfrequencies, as well as the extension of thermometry techniques [7] to this regime in extended mixed-species ion chains.

Secondly, we will perform a more precise measurement of the $^3P_0$ g-factor in In^+, which is determined by hyperfine-induced mixing of the ^3P-states and only known to within 5×10^{-3} [8]. By performing in-situ spectroscopic B-field measurements in mixed-species chains, we expect to reduce the uncertainty by at least one order of magnitude. The resulting improved knowledge of the B-field during clock operation will improve the applied 2nd-order Zeeman corrections to bring their uncertainty from 1.1×10^{-18} to the low 10^{-19} range.

[1] T. E. Mehlstäubler et al., Rep. Prog. Phys. 81, 064401 (2018)
[2] J. Grotti et al., Nature Physics 14, 437 (2018)
[3] S. M. Brewer et al., Phys. Rev. Lett. 123, 033201 (2019)
[4] J. Keller et al., Phys. Rev. A 99, 013405 (2019)
[5] T. Nordmann, PhD thesis, LU Hannover (2022)
[6] H. N. Hausser et al., arXiv: TBD (2024)
[7] I. Vyborni et al. PRX Quantum 4, 040346 (2023)
[8] T. Becker et al., IEEE Cat. No.01CH37172, 180 (2001)