



Recent Advances in High-Precision $^{40}\text{Ca}^+$ Optical Clocks: Laboratory-Based and Transportable Systems Pushing the Limits of Timekeeping

Hua Guan* ⁽¹⁾

(1) Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences
Wuhan, China, e-mail: guanhua@apm.ac.cn

In 2022, we reported our first-generation liquid-nitrogen-cooled Ca^+ optical clock with a systematic uncertainty of 3.0×10^{-18} [1]. Building upon this foundation, we have progressed to the research of the second-generation liquid-nitrogen-cooled $^{40}\text{Ca}^+$ optical clock, with the following major improvements: (1) Increasing the volume of the liquid nitrogen container to extend the interval for refilling liquid nitrogen to two days; (2) Optimizing the installation method and temperature measurement scheme for the Blackbody Radiation (BBR) chamber and ion trap; (3) Introducing the three-dimensional sideband cooling to the $^{40}\text{Ca}^+$ optical clock; (4) Measuring the ac magnetic field generated by the ion trap [2]. These efforts have paved the way for the systematic uncertainty of the $^{40}\text{Ca}^+$ ion optical clock to enter the 10^{-19} magnitude.

In parallel, we have developed a transportable $^{40}\text{Ca}^+$ optical clock designed for operation outside laboratory environments. With an estimated systematic shift uncertainty of 1.3×10^{-17} and a stability of $5 \times 10^{-15}/\sqrt{\tau}$, this system is a versatile tool for high-precision frequency measurements. To demonstrate its capabilities, the clock was transported from the Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, to the National Institute of Metrology, Beijing. Over 35 days, the absolute frequency of the 729 nm clock transition was measured, yielding a value of 411,042,129,776,400.26 (13) Hz with an uncertainty of 3.2×10^{-16} —a 1.7-fold improvement over previous results [3]. This achievement highlights the system's reliability and precision, positioning it as a competitive tool for global timekeeping and field-based metrology applications.

These advancements in both laboratory-based and transportable optical clocks underscore the rapid progress in optical frequency standards, paving the way for future redefinition of the SI second and enabling new possibilities in precision measurement science.

1. Huang, Yao, et al. "Liquid-nitrogen-cooled Ca^+ optical clock with systematic uncertainty of 3×10^{-18} ." *Physical Review Applied* 17.3 (2022): 034041.
2. Ma, Zixiao, et al. "Precision determination of the oscillating-magnetic-field-induced second-order Zeeman shift of a single- $^{40}\text{Ca}^+$ ion optical clock." *Physical Review A* 110.6 (2024): 063102.
3. Zhang, Huaqing, et al. "Absolute frequency measurements with a robust, transportable $^{40}\text{Ca}^+$ optical clock." *Metrologia* 60.3 (2023): 035004.