Progress on cadmium-ion and ytterbium-ion Microwave Frequency Standards at Tsinghua University

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The laser-cooled cadmium-ion microwave frequency standard has been developed at Tsinghua University for thirteen years. In 2013, we measured the ground-state hyperfine splitting frequency of $^{113}Cd^+$, and the precision was 5.7×10^{-13} [1]. In addition, we obtained preliminary short-term frequency instability to approximately $1.0 \times 10^{-12}/\sqrt{\tau}$ [2]. In 2015, the precision was further improved to 6.6×10^{-14}, and the short-term frequency instability was measured to be $6.1 \times 10^{-13}/\sqrt{\tau}$ [3]. In 2021, the performance of our cadmium-ion microwave frequency standard was improved once again. The second-order Zeeman frequency shift and its uncertainty was determined to be $1.05720(3) \times 10^{-10}$ due to the better magnetic shielding design, which is the most important factor among all factors that affect the performance of the $^{113}Cd^+$ clock. Finally, the ground-state hyperfine splitting frequency of $^{113}Cd^+$ was determined to be 15199862855.02799(27) Hz with a fractional frequency uncertainty of 1.8×10^{-14}, and the fractional frequency instability was measured to be $4.2 \times 10^{-13}/\sqrt{\tau}$ [4], which is close to the short-term instability limit estimated from the Dick effect. The result was consistent with previously reported values, but the measurement precision was four times better than the best result obtained to date.

To overcome the limits suffering from the Dick effect because of the dead time in the laser-cooling process and second-order Doppler frequency shift introduced by the ions rising temperature during interrogation, the sympathetic cooling technology was applied. In 2022, using laser-cooled $^{40}Ca^+$ as coolant ions, we developed a high-performance cadmium-ion microwave frequency standard. During the experiment, the $^{113}Cd^+$ ion crystal is cooled to below 100 mK and has a coherence lifetime of over 40 s. The short-term frequency instability reached $3.48 \times 10^{-13}/\sqrt{\tau}$ [5], which is comparable to that of the mercury ion frequency standard [6]. Its uncertainty was reduced to 1.5×10^{-14}, which was better than that of directly laser-cooled cadmium-ion microwave frequency standard.

Moreover, a microwave frequency standard based on laser-cooled $^{171}Yb^+$ ions has also been developed in our laboratory since 2021. More than 10^5 $^{171}Yb^+$ ions were stably trapped for over 40 hours. The short-term frequency instability of our system was measured to be $8.5 \times 10^{-13}/\sqrt{\tau}$. The ground-state hyperfine splitting frequency of $^{171}Yb^+$ was determined to be 12642812118.4674(8) Hz with a fractional frequency uncertainty of 6.33×10^{-14} [7]. Our work is in a continuous line with that of other scholars, while the short-term instability is promoted into a new record level.

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