Stability improvement of an aluminum ion optical clock

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***Abstract*—Based on the current initiative to redefine the SI "second", the optical clock has been demonstrated by many laboratories as a favorable candidate due to its excellent performance indicators. We describe the evaluation of uncertainty and optimization of stability in an aluminum-ion optical clock system based on quantum logic spectroscopy. The uncertainty evaluation of the current optical clock system is 1.6 × 10^{-18}. The frequency stability of a single system has been improved from 3.9 × $10^{-15}/\sqrt{\tau}$ to 2.6 × $10^{-15}/\sqrt{\tau}$ by using the servo-controlled self-comparison locking method.**

Keywords—ion optical clock, uncertainty, frequency stability, quantum logic spectroscopy

I. Introduction

As one of the most accurate measuring devices, optical frequency standards have extensive application prospects in testing relativity effect, measuring fundamental physical constants, and satellite navigation. With the continuous improvement of optical frequency standards demonstrated by various laboratories, the discussion on redefinition of the SI "second" has been put on the agenda, and the corresponding requirements are stipulated in published roadmap.

Due to its insensitivity to external electromagnetic field fluctuations, the fractional frequency uncertainty of the $^{27}Al^{+}$ ion optical clock developed by the National Institute of Standards and Technology (NIST) reaches 9.4 × 10^{-19} [1]. In 2021, the International Committee for Weights and Measures (CIPM) endorsed the conversion of $^{27}Al^{+}$ clock to a secondary representation of the "second" definition with a relative standard uncertainty of 1.9 × 10^{-16} [3]. However, the $^{27}Al^{+}$ ion optical clock is a relatively complex system, it involves more restrictions. Currently, only NIST meets the uncertainty requirements, with several other groups are also at an active stage of development [2][4][5][6][7]. It is of great significance to establish $^{27}Al^{+}$ ion optical clocks that meet the new definition of the "second" in various laboratories.

In this report, we describe the evaluation of uncertainty and optimization of stability in an aluminum-ion optical clock system based on quantum logic spectroscopy. Compared with the previous result [7] , the improvements mainly include the drift suppression of the biased magnetic field, the optimization of Raman sideband cooling, the signal-to-noise ratio improvement of the quantum logic spectrum, and the additional beam propagation noise compensation of the clock laser. The uncertainty evaluation [8] of the current optical clock system is 1.6 × 10^{-18}. After a period of closed-loop locking operation, the stability of the system is obtained. The Full Width at Half Maximum (FWHM) of the clock transition spectrum is observed to be 5.4(4) Hz within a detection time of 160 ms in the experiment. The frequency stability of a single system has been im-proved from 3.9 × $10^{-15}/\sqrt{\tau}$ to 2.6 × $10^{-15}/\sqrt{\tau}$ by using the servo-controlled self-comparison locking method.

II. Experimental Setup

Considering that the primary source of the uncertainty budget is the second-order Zeeman effect, the bias magnetic field is reduced to suppress the shift and its uncertainty. In addition, the drift compensation device is applied to provide feedback control to avoid the long-term magnetic field drift. The magnetic field fluctuation [9] experienced by ions is evaluated to be 35 μG, as shown in Fig. 1.

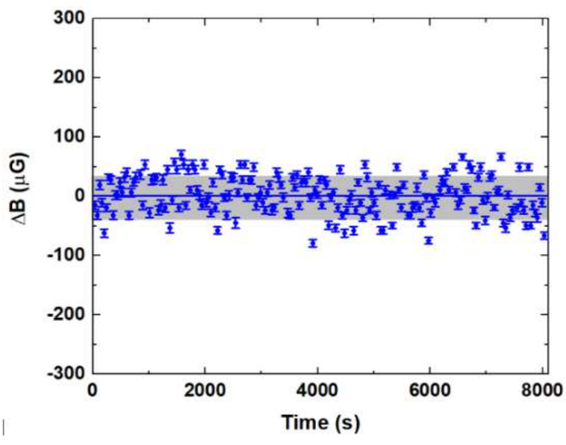

Fig. 1. Magnetic field noise perceived by ions after magnetic field compensation.

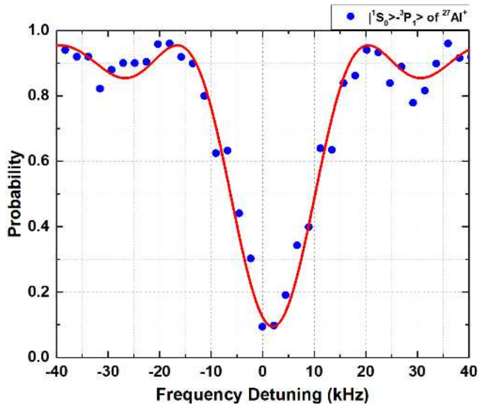

Fig. 2. $|^1S_0\rangle \rightarrow |^3P_1\rangle$ quantum logical spectrum of $^{27}Al^+$ ion.

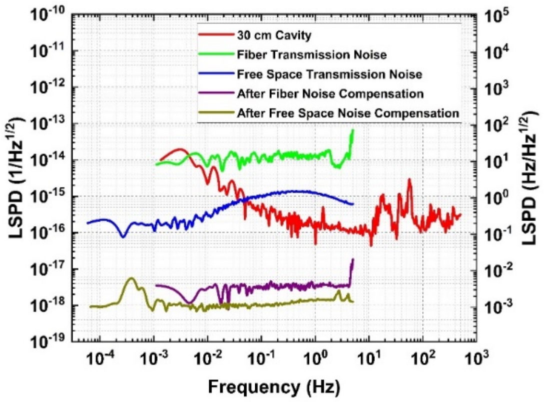

Fig. 3. LPSD of the clock laser and the beam propagation noise.

For $^{27}Al^+$ ion optical clocks, the detection of the quantum logic based clock transition has strong dependences on ions' vibrational states. The three-dimensional Raman sideband cooling technology is introduced to cool the ion pair to the vibrational ground state before detection. The quantum logic spectrum with high signal-to-noise ratio is shown in Fig. 2, which is mainly limited by the off-resonance transition of $^{25}Mg^+$ ion.

In addition, the clock laser at 1070 nm transmits through more than 30-meters-long optical fiber before frequency quadrupling to 267 nm, and the ultraviolet laser passes through several meters long free space optical beam path before illuminating the ion. The pick-up additional noise during transmission has influence on the stability of the clock laser and it is measured and suppressed experimentally. The LPSD (Linear Power Spectral Density) of the clock laser and the beam propagation noise are shown in Fig. 3.

III. Results

We achieved a clock transition signal with a relatively narrow linewidth and a high signal-to-noise ratio through optimization. The average dead time of each clock cycle in the experiment [8] is about 300 ms, corresponding to the collection time of each data point, is about 4.6 s. The FWHM of the clock transition spectrum was measured to be 5.4(4) Hz with a detection time of 160 ms, as shown in Fig. 4.

IV. Conclusions

Finally, we evaluated the optimized uncertainty [8] of the current optical clock system to be 1.6×10^{-18}, as shown inTABLE I. The frequency stability [8] of a single system has been evaluated to $2.6 \times 10^{-15}/\sqrt{\tau}$ by using the servo-controlled self-comparison locking method.

Since the current system stability is primarily limited by the quantum projection noise, our next step will concentrate on further improving the closed-loop locking period and the automatic operation of the system to increase the system's uptime operation rate. In addition, we will measure the absolute clock transition frequency and compare frequencies between two optical clocks to assess the long-term stability of our optical clock.

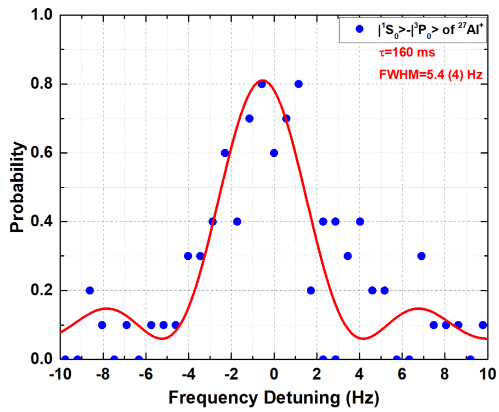

Fig. 4. The $|^1S_0\rangle \rightarrow |^3P_0\rangle$ transition spectrum of $^{27}Al^+$ ion.

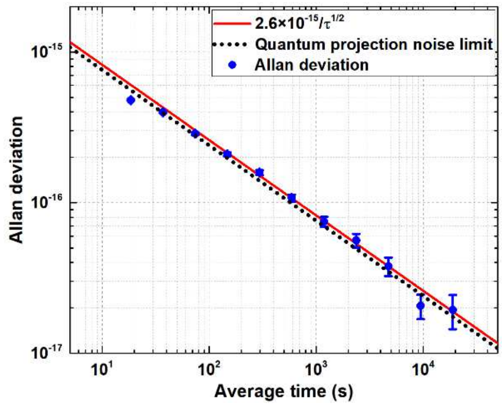

Fig. 5. Stability results of $^{27}Al^+$ ion optical clock system under closed loop locking.

TABLE I. RELATIVE FREQUENCY SHIFT AND UNCERTAINTY EVALUATION OF CURRENT $^{27}Al^+$ ION OPTICAL CLOCK.

Contribution	Correction (10^{-18})	Uncertainty (10^{-18})
Excess micromotion	-7.4	0.8
Secular motion	-1.3	0.4
Quadratic Zeeman	-3285.1	1.2
Frist-order Doppler	0	0.1
AOM phase chirp	0	0.1
Blackbody radiation	-3.3	0.5
Laser Stack	0	＜0.1
Background gas collisions	0	＜0.1
Electric quadrupole	0	＜0.1
Total	-3297.1	1.6

REFERENCES

[1] S. M. Brewer, J. S. Chen, A. M. Hankin, E. R. Clements, C.W. Chou, D. J. Wineland, D. B. Hume, and D. R. Leibrandt, "$^{27}Al^+$ quantum-logic clock with a systematic uncertainty below 10^{-18}," Phys. Rev. Lett. **123**, 033201 (2019).

[2] K. F. Cui, S. J. Chao, C. L. Sun, S. M. Wang, P. Zhang, Y. F. Wei, J. B. Yuan, J. Cao, H. L. Shu, and X. R. Huang, "Evaluation of the systematic shifts of a $^{40}Ca^+$-$^{27}Al^+$ opticalclock," Eur. Phys. J. D **76**, 140 (2022).

[3] Recommended values of standard frequencies (2021), https://www.bipm.org/en/publications/mises-en-pratique/standard frequencies-second.

[4] S. Hannig, L. Pelzer, N. Scharnhorst, J. Kramer, M. Stepanova, Z. T. Xu, N. Spethmann, I. D. Leroux, T. E. Mehlstäubler, and P. O. Schmidt, "Towards a transportable aluminium ion quantum logic optical clock," Rev. Sci.Instrum. **90**, 053204 (2019).

[5] M. Guggemos, M. Guevara-Bertsch, D. Heinrich, O. A. Herrera-Sancho, Y. Colombe, R. Blatt, and C. F. Roos, "Frequency measurement of the $^1S_0$, F = 5/2 $\leftrightarrow ^3P_1$, F = 7/2 transition of $^{27}Al^+$ via quantum logic spectroscopy with $^{40}Ca^+$," New J. Phys. **21**, 103003 (2019).

[6] K. Ksenia, Z. Ilia, S. Ilya, B. Alexander, and K. Nikolay, in 2018 European Frequency and Time Forum (EFTF) (IEEE, Turin, Italy, 2018), Vol. 377.

[7] Z. Y. Ma, H. L. Liu, W. Z. Wei, W. H. Yuan, P. Hao, Z.Deng, H. Che, Z. T. Xu, F. H. Cheng, Z. Y. Wang, K. Deng, J. Zhang, and Z. H. Lu, "Investigation of experimental issues concerning successful operation of quantum-logicbased $^{27}Al^+$ ion optical clock," Appl. Phys. B **126**, 129 (2020).

[8] Z. Y. Ma, et al., "Quantum-logic-based $^{25}Mg^+$-$^{27}Al^+$ optical frequency standard for the redefinition of the SI second," Phys. Rev. Applied **21**, 059901 (2024).

[9] Wenzhe Wei, et al., "Measurement and suppression of magnetic field noise of trapped ion qubit," J. Phys. B: At. Mol. Opt. Phys. **55**, 075001 (2022).