A Microwave Clock Based on Laser-Cooled $^{171}Yb^{+}$ Ions

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***Abstract*—A microwave frequency standard based on laser-cooled $^{171}Yb^{+}$ ions at Tsinghua University has been investigated. More than 10^5 $^{171}Yb^{+}$ ions were stably trapped for over 40 hours. The ground-state hyperfine splitting frequency of $^{171}Yb^{+}$ was determined to be 12642812118.4672(8) Hz with a fractional frequency uncertainty of 6.33×10^{-14}. Our work is in a continuous line with that of other scholars.**

Keywords—microwave clock; ytterbium ions; laser cooling

I. Introduction

Microwave frequency standards are extensively used in fields including satellite navigation[1], deep space exploration[2], and time keeping[3]. Especially, transportable microwave clocks based on laser-cooled ions bring promising performance and are widely studied for the past few decades. At Tsinghua University, our team has been continuously committed to the research of trapped ion microwave clocks and has made great progress on the cadmium ion microwave clock[4, 5]. This paper reports the apparatuses for a microwave ion clock and progresses toward a microwave frequency standard based on laser-cooled $^{171}Yb^{+}$ ions, established at Tsinghua University. Owing to the excellent vacuum (<10^{-9} Pa), more than 10^5 ions are stably trapped and the life time is expected to reach 40 hours. According to previous investigation[6], the short-term instability of our system was measured to be 8.5×10-13/$\tau^{0.5}$ for averaging times between 10 and 1000 s. After carefully estimating primary shifts and uncertainties, the ground-state hyperfine splitting frequency of $^{171}Yb^{+}$ is determined to be 12642812118.4672(8) Hz with a fractional frequency uncertainty of 6.33×10^{-14}.

II. Experiment Setup

Experimental apparatus has been meticulously described elsewhere [6]. The system is demonstrated briefly here, as shown in figure 1. The electronics, lasers, and magnetic shields are integrated into a single physical package. Titanium sublimation pump is used to obtain better vacuum. Ions are supposed trapped within a linear Paul trap. Four group of Helmholtz coils are used to compensate the geomagnetic field and destabilize the dark states[7]. A three layers of magnetic shield is used to minimize the fluctuation of the geomagnetic field.

The 369 nm, 935nm and 399 nm lasers are used to achieve ion cooling, pumping, and detection. Lasers can be inflected in the trap from upside and downside.

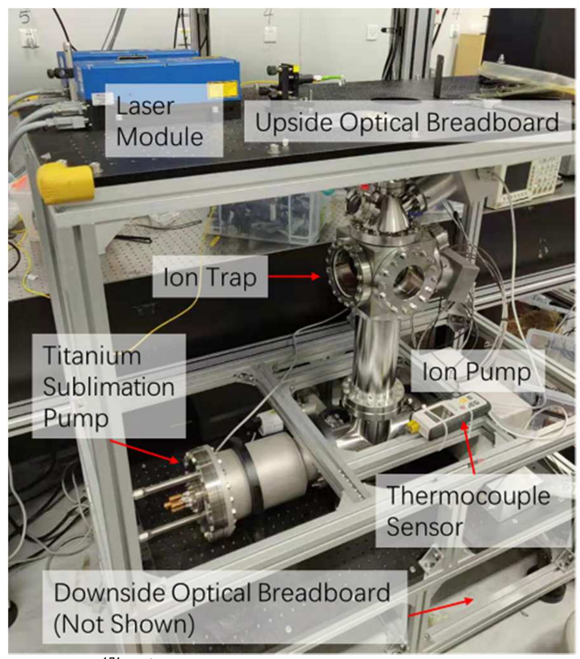

Fig. 1. Picture of $^{171}Yb^{+}$ microwave clock. Titanium sublimation pump is used to obtain better degree of vacuum. Lasers can be inflected in the trap from upside and downside. The larger vacuum chamber is chosen to facilitate convenient replacement of the atomic oven and electron gun.

Lasers setup is depicted in figure 2. 369nm lasers is used for ion ionization and ion cooling. 399nm laser is used for isotope selection and ion ionization. 935nm laser is used to drive ions out of the long-lived state $^2D_{3/2}$ $(F=0)$. All accurate wavelengths of different lasers, corresponding to different state transition, are found by the saturated absorption spectroscopy, obtained from a Yb hollow cathode lamp (HCL), and are measured and stabilized by a high-resolution wavemeter (High Finesse WSU-8) together with a proportional-integral-derivative(PID) controller.

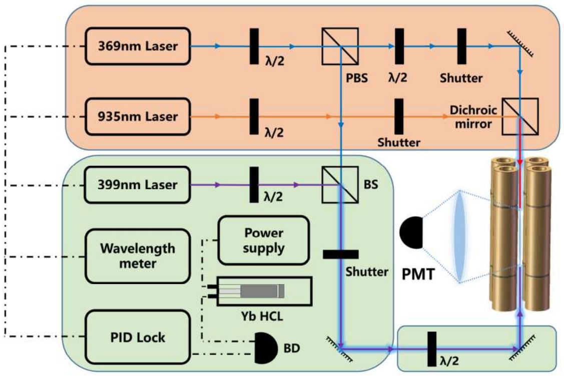

Fig. 2. Laser system.

III. RESULTS AND DISCUSSION

More than 10^5 ions are trapped after ion load[6]. Photon counts at the half waist of the Ramsey fringe has also been recorded for several hours, which is used to measure the loss rate of ions. The fit curve shows that the lifetime constant of trapped ions is over 40 hours (shown in figure 2).

Based on previous effort, we have estimated some primary shifts and uncertainties, including Second-order Zeeman shift (SOZS), Second-order Doppler shift (SODS), Blackbody radiation shift, Quadratic Stark shift, Gravitational redshift, Pressure shift, and Light shift [6]. Among all shifts, SOZS shift is supposed to be accurately evaluated again, and reference shift, resulting from H-maser reference, should be given to determine the ground-state hyperfine splitting frequency of $^{171}Yb^+$.

To reassessed the SOZS, we have measured frequencies of the magnetic-field-sensitive transitions of ($^2S_{1/2}$(F=1, m_F=0) →$^2S_{1/2}$(F=1, m_F=1) and ($^2S_{1/2}$(F=1, m_F=0) →$^2S_{1/2}$(F=1, m_F=-1), v_{01} and v_{0-1}, respectively. Figure 3 shows a typical Rabi fringe of one of the magnetic-field sensitive transitions.

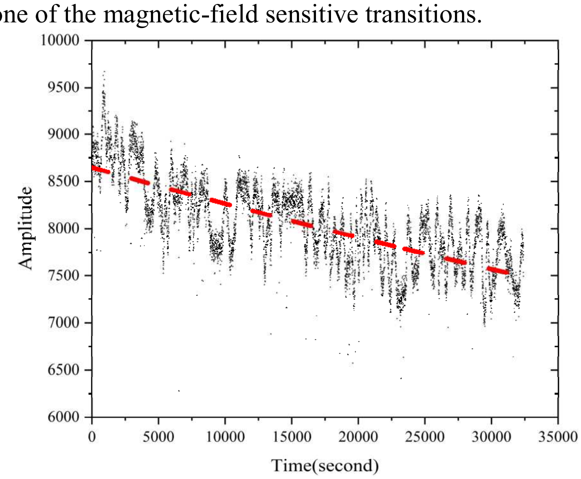

Fig. 2. Photon counts at the half waist of the Ramsey fringe; the background photon counts is about 3000.

According to the Breit-Rabi formula, under the zero magnetic field, the central frequency of transition ($^2S_{1/2}$(F=1, m_F=0)→$^2S_{1/2}$(F=1, m_F=0), v_{00} can be expressed as:

$$v_{00}(0) = \sqrt{v_{00}(B_0) - (\frac{g_J - g_I}{g_J + g_I})^2 (v_{01} - v_{0-1})^2} \quad (1)$$

where $v_{00}(B_0)$ is the central frequency of transition ($^2S_{1/2}$(F=1, m_F=0)→$^2S_{1/2}$(F=1, m_F=0) under a static magnetic B_0, g_J=2.0023[8], g_I=5.3577×10^{-4}[8], $|v_{01}-v_{0-1}|$ is obtained to be 288278(31) Hz.

Since the Allan data[6] at 1000 s is below 2.98×10^{-14}, the $v_{00}(B_0)$ is measured to be 12642812121.75038(37) Hz. Then the second-order Zeeman frequency shift (SOZS) is 259686.1394×10^{-15} with an uncertainty of 56×10^{-15}.

Aiming at the frequency reference, an active hydrogen, the fractional frequency difference between the active hydrogen clock and UTC is 4.4(5)×10^{-14}. While the difference between UTC and the primary frequency standards (PFS) is -0.16(12) ×10^{-15}. Therefore, the fractional frequency shift due to the reference is 4.4(5)×10^{-14}.

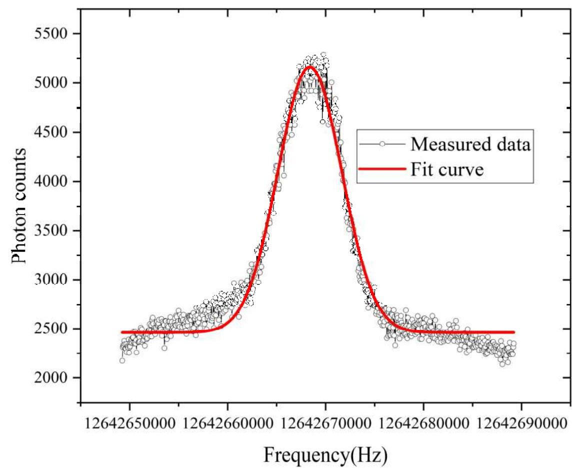

Fig. 3. Rabi lineshape of the magnetic-field-sensitive transition $v_{01}(B_0)$ with a p microwave pulse time of 60 ms. The power of the microwave pulse is -3dBm. The scanning step length is 400 Hz.

Here, based on previous effort, the main shifts and uncertainties are updated listed in table 1.

Table 1 Estimated Fractional Systematic Frequency Shifts and Uncertainties

Shift type	Correction (10^{-15})	Uncertainty (10^{-15})
Second-order Zeeman shift(SOZS)	259686.1394	55.7
Second-order Doppler shift (SODS)	-35	3
Quadratic Stark shift	-0.6	0.3
Black body radiation shift	-10	1
Gravitational redshift	4.7	0.1
Pressure shift	0	0
Light shift	0	0
Reference shift	43.9	5
Total	259685.2168	56

Finally, the 0-0 ground-state hyperfine splitting frequency of $^{171}Yb^+$ is determined to be $v_{00}(0)$ = 12642812118.4672(8) Hz. This result is in a continuous line with that of other scholars, as is shown in table 2.

In this study, we have reassessed the reference shift and SOZS shift. By updating all primary shifts and uncertainties, the 0-0 ground-state hyperfine splitting frequency of $^{171}Yb^{+}$.

Table 2 Comparison of Different Measurement Results

Ref	Measurement result (Hz)	Uncertainty (10^{-14})
[1][9]	12642812118.471(9)	71.1
[2][10]	12642812118.466(2)	15.8
[3][11]	12642812118.4685(9)	7.12
[4][12]	12642812118.4682(4)	3.16
This work	12642812118.4672(8)	6.33

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