Cooling and Crystallization of Trapped Single $^{171}Yb^+$ Ion for Optical Frequency Standard

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***Summary*—By measuring the frequencies emitted as atoms transition between energy levels, atomic frequency standards are among the most advanced devices available for keeping time. Here, we report our recent progress in developing an optical frequency standard based on a single $^{171}Yb^+$. With the laser Doppler cooling, a single ytterbium ion is cooled to crystallization and the temperature of the ion crystal is estimated to be below 1 mK. The progress reported in this paper is the first step of the project and paves the way for future development.**

Keywords—Optical Frequency Standard; Laser Cooling; Ion Trapping

I. Introduction

Trapped single ion has excellent isolation from the external field, and is considered to be the purest quantum system that human beings can achieve. Single-ion optical frequency standards can achieve ultra-high accuracy [1,2,3] and play an important role in the definition of seconds [4], the inspection of fundamental physics [5], and the exploration of new physics [6]. $^{171}Yb^+$ has the advantage of two narrow linewidth optical reference transitions. Frequency standard based on the electric quadrupole $^2S_{1/2}$ - $^2D_{3/2}$ transition [7,8] was identified as one of the minor representations of SI seconds. The practical optical clock project of the Federal Ministry of Education and Research in Germany (BMBF) is also based on the electric quadrupole transition of the $^{171}Yb^+$ ion [9]. Electric octupole $^2S_{1/2}$ - $^2F_{7/2}$ transition was originally studied at the National Physical Laboratory in the UK [2,10]. The remarkable character of this transition stems from the long natural lifetime of the $^2F_{7/2}$ state. Since octupole transitions can be resolved with line widths that are virtually unaffected by spontaneous decay and determined only by laser stability, frequency standards based on single-ion with very low quantum projection noise instability can be achieved. Measurements of the frequency ratio of the quadrupole and the octupole transitions in one trapped $^{171}Yb^+$ ion would be a convenient way to test the variation of the fine structure constant α. Our group has 12 years of experience in developing microwave frequency standards based on trapped $^{113}Cd^+$ ions [11-20] and $^{171}Yb^+$ ions [21]. Here, we report our recent progress in developing an optical frequency standard based on trapped single $^{171}Yb^+$ ion. Laser cooling and crystallization of trapped single $^{171}Yb^+$ ion were achieved. The temperature of a single $^{171}Yb^+$ ion is estimated to be below 1 mK, thereby aiding a suppression of the second-order Doppler shift.

II. Methods & Results

The single $^{171}Yb^+$ ion is trapped in a linear Paul trap which consists of six electrodes, as shown in FIG. 1. Four cylindrical electrodes act as radio frequency (RF) electrodes for radial confinement; two tapered electrodes act as endcap (EC) electrodes for axial confinement; two extra cylindrical electrodes act as compensate (CMP) electrodes for the compensation of stay electric field and reducing micromotion of ion. All electrodes have diameters of 0.5 mm, and the radial distance from the EC and the closest surface of the RF electrodes is 0.21 mm. The distance of two EC electrodes is 4 mm. Ultra-high vacuum in a vacuum chamber (4.50" spherical octagon vacuum chamber, Kimball Physics) is maintained by a combination nonevaporable getter (NEG) and ion-getter pump (NEXTorr Z200), with the background pressure being around 2×10^{-9} Pa.

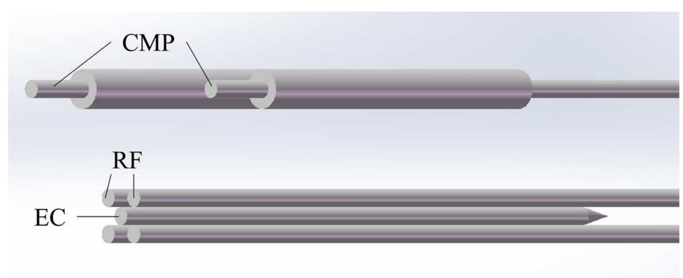


Fig. 1 Diagram of the linear Paul trap

Energy levels of ^{171}Yb and $^{171}Yb^+$ are shown in FIG. 2. Lasers operating at wavelengths of 399-nm and 370-nm are used to photoionize neutral ^{171}Yb atoms. The 370 nm laser beam is used for Doppler cooling the $^{171}Yb^+$ ion. Two repump laser beams of wavelengths 935-nm and 760-nm are used to repump the $^{171}Yb^+$ ion from the $^2D_{3/2}$ and $^2F_{7/2}$ dark states. A 3.06-GHz and 5.2-GHz microwave sidebands are applied to the 935-nm and 760-nm laser beams by fiber electro-optic modulator (EOM) to eliminate the hyperfine dark state of the $^2D_{3/2}$ and $^2F_{7/2}$ level, respectively. The 370-nm and the 399-nm laser beams and the 935-nm and 760-nm laser beams are combined by the polarization beam splitter respectively and transmitted to the vacuum chamber through the fiber couplers and single-mode fibers. Laser beam output from the fiber collimators is focused on the $^{171}Yb^+$ ion through lenses installed on translation stages. The waists of the focused laser beams are around 50 μm. The frequencies of laser beams are stabilized to a high-precision wavelength meter (HighFinesse WS8-2) by a proportional–integral–derivative controller. The wavelength meter can further be calibrated using an ultra-stable "clock laser".

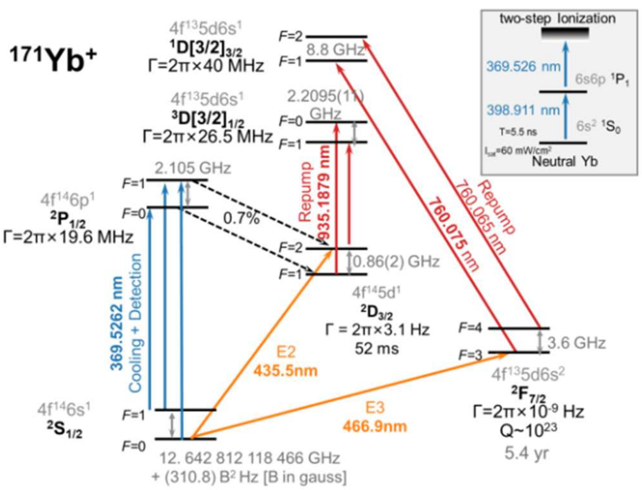


Fig. 2 Energy levels of ^{171}Yb and $^{171}Yb^+$ [22].

A 6-Gauss magnetic field is generated by a permanent magnet which installed near the vacuum chamber. The direction of the strong magnetic field forms an angle of 30 degrees with the 370-nm laser beam to induce a precession in the dipole moments of the ions and to destabilize the Zeeman dark states of the $^2S_{1/2}$ (F=1) level [23]. Even so, ion still can leak into the dark state because of polarization impurity of the cooling laser. Hence, a 12.6-GHz microwave radiation (Agilent E8257D) with 23-dBm power, resonant with the transition of $^2S_{1/2}|F=0, m_F=0\rangle \leftrightarrow {}^2S_{1/2}|F=1, m_F=0\rangle$ is applied to repump the ion in the dark state $^2S_{1/2}$ ($F = 0$) back to the useful $^2S_{1/2}$ ($F = 1$) state. The preliminary physical and laser system of the $^{171}Yb^+$ ion optical frequency standard is shown in FIG. 3 and 4.

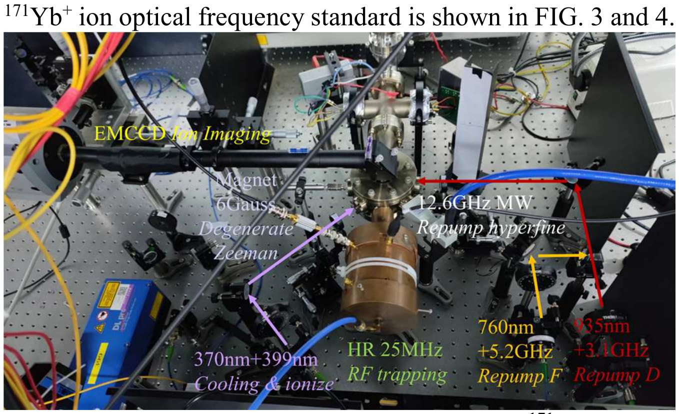


Fig. 3 Physical system (1st Lab version) of the $^{171}Yb^+$ ion optical frequency standard

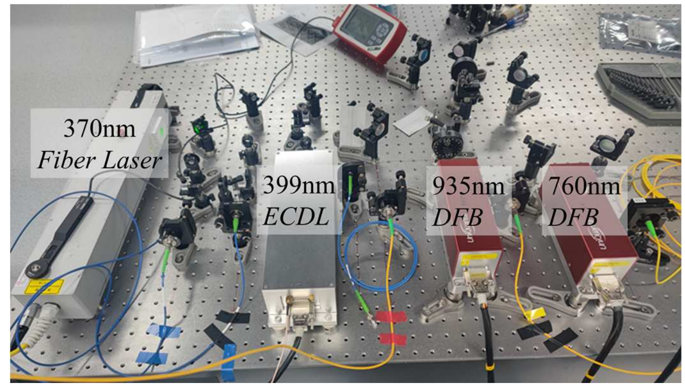


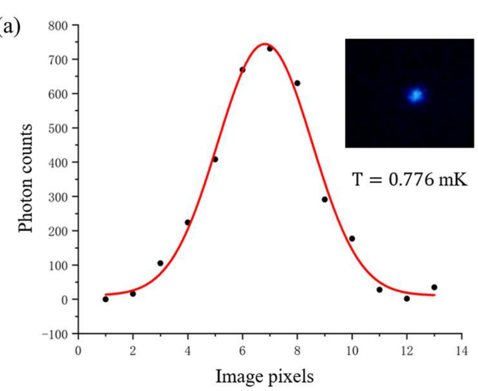
Fig. 4 Laser system (1st Lab version) of the $^{171}Yb^+$ ion optical frequency standard

The $^{171}Yb^+$ ion fluorescence with a wavelength of 370 nm is divided into two parts by a 50:50 beam splitter, which are collected by a photomultiplier tube (PMT, Hamamatsu H11890-210) and imaged by an electron multiplying charge-coupled device (EMCCD, Andor iXon Ultra 888) respectively. The temperature of the single $^{171}Yb^+$ ion is roughly estimated through the EMCCD image. The image of ion is the convolution of the point-spread function (PSF) and the fluorescence of the ion [24,25]. The width of such a Gaussian type of image can be expressed as

$$\sigma_{CCD}^2 = \sigma_{PSF}^2 + M^2\sigma_i^2 \tag{1}$$

where σ_{CCD} is the width of the EMCCD image, σ_{PSF} is the width of the PSF caused by the diffraction of the imaging system, M is the magnification of the imaging system, and σ_i is the width of the fluorescence of the ion. In our system, M is measured to be 5.96 and σ_{PSF} is calculated to be 2.38 μm from the parameters of the camera (Nikon PF10545MF-UV) and the optical diffraction limit of the fluorescence wavelength. The fitted result of the single $^{171}Yb^+$ image is shown in FIG. 5, and the temperature of the single $^{171}Yb^+$ ion is estimated to be around 0.8 mK which close to its Doppler cooling limit. The temperature of multi $^{171}Yb^+$ ions is also estimated to be below 1 mK, which indicate a low heating rate of our ion trap. A low temperature of ion aiding a suppression of the second-order Doppler shift of uncertainty.

(a)



(b)

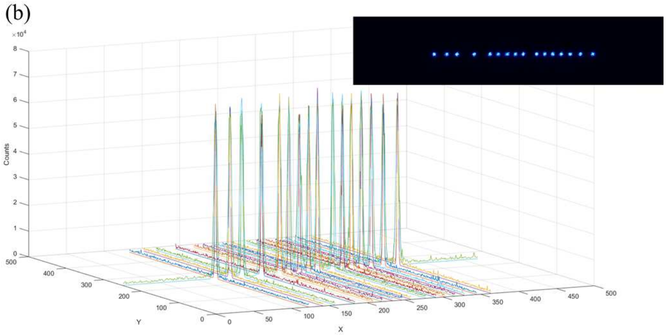


Fig. 5 The EMCCD signal and the estimated temperature of (a) single $^{171}Yb^{+}$ ion and (b) multi $^{171}Yb^{+}$ ions.

III. Conclusion

The recent progress of developing an optical frequency standard based on a single $^{171}Yb^{+}$ ion was reported in this paper. The first version of the ion trap, the vacuum system, the laser system, and the imaging system were designed and developed. The signal of crystallized single $^{171}Yb^{+}$ was successfully observed. The temperature of a single $^{171}Yb^{+}$ ion was roughly estimated to be around 0.8 mK using EMCCD. The progress reported in this paper is the first step of the optical frequency standard project at "THU & BIRMM" and paves the way for future development.

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