Development of Two Single-Ion Spectroscopy Systems for the $^2S_{1/2} - {}^2D_{5/2}$ transition in Ytterbium Ions Towards Measurement of Isotope Shifts

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***Summary*—We are developing two systems for single-ion spectroscopy of the $^2S_{1/2} - {}^2D_{5/2}$ transition in Yb^+. We develop three-dimensional cooling technique and evaluate it from single-ion spectra of the transition. We establish isotope-selective single-ion loading towards measurement of the isotope shifts of the transition.**

Keywords—Ytterbium ion; ion trap; optical clock

I. INTRODUCTION

Singly ionized ytterbium ion (Yb^+) has attractive transitions used for the references in optical clocks [1,2] and tests of fundamental physics [3-6]. We have so far realized single-ion spectroscopy of the $^2S_{1/2} - {}^2D_{3/2}$ transition in $^{171}Yb^+$ [7]. The temperature of a single $^{171}Yb^+$ ion was 7 mK and higher than the Doppler cooling limit of ~0.5 mK. To improve the laser cooling, we introduced two cooling beams propagating in different directions and minimized excess micromotions in three dimensions using another ion trap setup. The temperature was evaluated using single-ion spectroscopy of the $^2S_{1/2} - {}^2D_{5/2}$ transition in $^{174}Yb^+$ [8].

Following these works, we are developing two systems for single-ion spectroscopy of optical clock transitions in Yb^+. Comparison of the transition frequencies between two systems is essential for evaluation of uncertainties and is useful for some measurements in tests of fundamental physics. We aim at measurement of the isotope shifts in the $^2S_{1/2} - {}^2D_{5/2}$ transition. The isotope shifts of the transition have been measured with uncertainties of ~300 Hz [9]. Measurements of improved uncertainties has been presented in this conference [10].

II. METHODS

Laser cooling is performed using the $^2S_{1/2} - {}^2P_{1/2}$ transition at 370 nm. Yb^+ decays from the $^2P_{1/2}$ to the $^2D_{3/2}$ state with a branching ratio of $\sim 7 \times 10^{-3}$. We drive the $^2D_{3/2} - {}^3D[3/2]_{1/2}$ transition at 935 nm to close the cooling cycle. We drive the $^2S_{1/2} - {}^2D_{5/2}$ transition at 411 nm as a clock transition. Yb^+ in the $^2D_{5/2}$ state decays to the $^2F_{7/2}$ state with a branching ratio of 0.8. The lifetime of the $^2F_{7/2}$ state is several years. We detect the excitation to the $^2D_{5/2}$ state via electron shelving in the $^2F_{7/2}$ state. To repeat the excitation of the clock transition and measure the excitation probability, we deexcite Yb^+ from the $^2F_{7/2}$ state by driving the $^2F_{7/2} - {}^1D[5/2]_{5/2}$ transition at 638 nm.

The experimental setup is developed from that used in our previous work [7]. We use two RF traps of the same electrode shape of a conical cut and the inner diameter of the ring electrode of 0.8 mm. We apply RF voltages of the frequency and the amplitude of ~14 MHz and ~100 V, respectively. We introduce four compensation electrodes to minimize excess micromotions. The oven in the first setup contains enriched ^{174}Yb metal, while a natural isotope mixture in the second setup.

The cooling radiation at 370 nm is generated by sum-frequency mixing of two extended-cavity laser diodes (ECLDs) at 671 nm and 822 nm using a power build-up cavity resonant to the two fundamental frequencies. The sum frequency is stabilized as follows; The 822-nm ECLD is locked to a resonance of a Fabry-Perot cavity and loosely offset locked to the master laser in the clock laser system described below. Then, the power build-up cavity is stabilized to the stabilized 822-nm ECLD and the 671-nm ECLD is locked to the stabilized cavity. An ECLD at 935 nm is used for the repumping laser.

For the first system, the clock laser is composed of a master laser line-narrowed to a resonance of a high-finesse cavity, a slave laser phase locked to the master laser with an offset frequency, and second-harmonic generation of the slave laser using a power build-up cavity. The offset frequency for the phase locking is scanned to take the spectrum of the clock transition. The linewidth of the master laser, evaluated from the beat spectrum between similar two systems, is below 500 Hz.

III. RESULTS

To operate two systems simultaneously, it was desirable to increase the power of the cooling laser. We exchanged the LBO crystal for the sum-frequency mixing to more transparent one.

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The output power is twice as large as before, i.e., 120 – 200 μW. We have so far observed no degradation in the sum-frequency power during three-year operation. We succeeded in simultaneous laser cooling of $^{174}Yb^+$ ions independently trapped in the two RF traps.

To enable to measure the isotope shifts of ~5.8 GHz at the maximum in the $^2S_{1/2}$ – $^2D_{5/2}$ transition [9], we developed a second clock laser system using another offset locked laser. We used the same master laser as a reference, then we phase locked another ECLD to the master laser. We measured the residual phase noise to be 0.07 rad from the integration of the power spectral density of the phase noise in the beat at the offset frequency between 10 Hz and 10 MHz. By temperature control of the ECLD, we achieved continuous phase locking over twelve hours. We generated second harmonics of 68 μW from the fundamental power of 52 mW in a 10 mm-long periodically-polled KTP crystal using a single-pass focused beam. Eliminating the servo-loop for the power build-up cavity contributes to a reliable long-term continuous operation required for future frequency measurements.

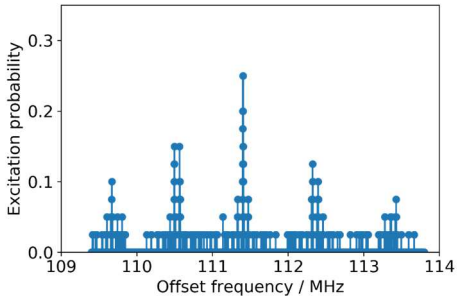

Fig. 1 Typical spectrum of the $^2S_{1/2}$ – $^2D_{5/2}$ transition of single $^{174}Yb^+$ in the first setup.

As for the experiments using the RF traps, we repeat the single-ion spectroscopy of the $^2S_{1/2}$ – $^2D_{5/2}$ transition in $^{174}Yb^+$ using the first system. A typical spectrum is shown in Fig. 1. To cool the ion three dimensionally, we introduce two cooling beams propagating in different directions. We minimize excess micromotions three dimensionally; We detect rf-photon cross correlation using two cooling beams. The residual undetectable excess micromotion perpendicular to the two cooling beams is minimized by reducing the fluorescence intensity modulation synchronized to the potential modulation. The minimum temperature, estimated from the relative sideband intensity, so far achieved is 0.9 mK. However, the temperature varies in each measurement. We are continuing the spectroscopy to reveal the factors of determining the achievable temperature.

We achieved isotope-selective loading of all even isotopes from a natural isotope mixture using a larger RF trap of an inner diameter of the ring electrode of 5 mm [11]. Following this, using the second system, we trapped single ions of all even isotopes. Figure 2 shows one-by-one loading of the rarest isotope of $^{168}Yb^+$. Its natural abundance is 0.13 %. We are currently improving laser cooling using two cooling beams also in this trap.

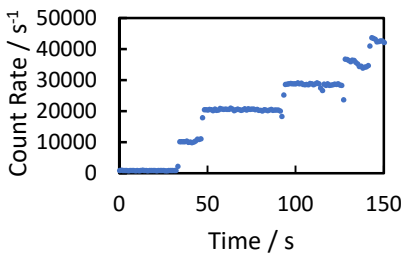

Fig. 2 One-by-one loading of $^{168}Yb^+$ ions

IV. Conclusions

We are developing two setups for single-ion spectroscopy of the $^2S_{1/2}$ – $^2D_{5/2}$ transition of Yb^+ for measurement of isotope shifts. We will proceed single-ion spectroscopy using the second system and then conduct simultaneous detection of the spectra using the two systems.

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