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Experimental confirmation of micromotion shift cancellation via operation at trap magic frequency and reduction in evaluated systematic uncertainties for the $^{88}\text{Sr}^+$ optical frequency standard at 445 THz

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Abstract — We describe recent experiments and results which show the effective cancellation of micromotion induced systematic shifts for the 445-THz reference transition in a trapped and laser cooled $^{88}\text{Sr}^+$ single ion reference. Using two different ion trap systems based on a Paul and endcap design, the critical or magic frequency at which micromotion effects cancel has been effectively measured at 14.4 MHz. This work also allows an improved determination of the polarizability difference of the ground and excited states and an improvement in the evaluated blackbody shifts to the low 10^{-17} level.

Index Terms — Clocks, frequency control, ions, lasers, laser stability, precision measurements, spectroscopy, Stark effect, strontium.

I. INTRODUCTION

Ultra-low uncertainty and stable optical frequency standards which are referenced on dipole-forbidden transitions in laser cooled single ions or collections of neutral atoms now have evaluated uncertainties and stabilities superior to those obtained by the best Cs fountain realizations of the SI second. In particular, standards based on single, trapped, and laser cooled ions are being actively studied due to their close approximation to an isolated and unperturbed atomic system. One of the single ion systems having the potential for extremely low evaluated uncertainty and straightforward implementation is the electric quadrupole allowed $5s\ ^2S_{1/2} - 4d\ ^2D_{5/2}$ transition in $^{88}\text{Sr}^+$ whose reference frequency is at 445 THz (674 nm) and having a natural linewidth of 0.4 Hz [1,2]. All transitions for the needed laser cooling, state repumping and reference lasers exist in the visible or near infrared region of the spectrum and such sources are now available commercially.

Recently, a detailed uncertainty analysis was performed on our existing NRC endcap trap based frequency standard which resulted in a total estimated fractional frequency uncertainty of 2.3×10^{-17} [1]. A critical advantage in the reported work was the operation of the standard at a trap frequency where the micromotion induced second order Doppler (time dilation) and Stark shifts yield equal and opposite contributions and thus cancel. It was also observed that the principal current limitation in evaluated uncertainty is the blackbody radiation

shift. The current limitation in the blackbody shift evaluation is the present level of uncertainty in the value of the differential scalar polarizability for the reference transition [3].

In this work, we have implemented a precision measurement of the trap critical frequency by operating two independent ion trap systems: one based on an endcap trap, the other an upgraded version of a previous employed Paul trap system. The endcap trap system is maintained under low micromotion perturbation while the Paul trap system exposes its ion to a relatively constant source of micromotion. Comparing the 445-THz transition frequency of the two traps as a function of Paul trap operating frequency allows one to find the critical or ‘magic’ trap frequency at which such micromotion perturbations cancel to high accuracy.

II. OVERVIEW OF EXPERIMENT

Single $^{88}\text{Sr}^+$ ions are maintained in two independent trapping systems located in different rooms. The endcap trap system employed has a characteristic endcap separation of $2z_0 = 0.54$ mm and is operated at a trap frequency of 14.39 MHz with a peak-to-peak voltage amplitude of 215(3) V. The ion can be probed along three orthogonal directions and have its micromotion monitored and adjusted to the 10^{-18} level [1]. The trap system is constructed with low emissivity materials and the endcap surfaces are highly polished to reduce sensitivity to blackbody contributions to the uncertainty via the change in electrode temperature due to rf heating. Single ion storage times over one week have now been obtained together with continuous probing of the reference transition for periods over 24 hr.

The Paul trap based system is an upgraded version of the trap system originally used at NRC to study the $^{88}\text{Sr}^+$ ion [4]. The trap electrodes are manufactured out of tantalum and have a characteristic center to endcap distance of $z_0 = 0.5$ mm and centre to ring electrode of $r_0 = 0.71$ mm. The ion is probed and laser cooled along a single direction via propagation in the gap between the endcap and ring electrode. Operation of the trap can be performed at any trap frequency between 10 to 15.5 MHz. In these experiments, the trap voltage amplitude was adjusted to maintain a constant level of micromotion to

the second test ion by keeping a constant value for the trap stability parameter q_i [1] as the frequency was varied.

Both traps are probed using a stable 445-THz laser diode system which consistently yields transform limited probing of the ion down to the 4-Hz level with drift rates of 10 mHz/s [5]. Independent optical fibers transport the radiation from the probe laser system to the two ion trap systems. Rf synthesizers at each trap then drive an acousto-optic modulator to shift the radiation into resonance of the respective clock transition. Each system has its own fiber noise cancellation to reduce fiber induced phase noise on the probe radiation. The two traps are also fed from a common 422-nm diode laser source providing laser cooling, a 1092-nm laser for repumping, and a 1033-nm source for state clearout of the upper state of the $4d^2D_{5/2}$ reference transition when the atom undergoes an excitation. The ion is loaded into the trap using photoionization of a weak effusive beam of neutral Sr. In this way, reloading is obtained with very little change of the micromotion condition of each trap.

III. RESULTS

To lowest order, the micromotion frequency shifts due to the second order Doppler effect and Stark effect yield an average combined shift of

$$\frac{\Delta \nu_\mu}{\nu_o} = -\frac{\langle E^2(t) \rangle}{2} \left[\left(\frac{e}{m\Omega c} \right)^2 + \frac{\Delta \alpha_o}{h\nu_o} \right]. \quad (1)$$

where the term $\langle E^2(t) \rangle$ is the mean squared electric field seen by the ion, $\Delta \alpha_o$ is the polarizability difference of the upper and lower state of the reference S-D transition, Ω is the trap angular drive frequency, m is the ion mass, and ν_o is the transition frequency. Using the $\Delta \alpha_o$ value determined in [3], the ion trap frequency at which cancellation of the net micromotion effects occur gives a value of $\Omega/2\pi = 14.39(25)$ MHz. Figure 1 shows the initial results of the comparison between the two ion trap systems confirming the effective variation in the level of observed micromotion shift in the Paul trap system and the cancellation of such effect when the trap is operated at the trap ‘magic’ frequency of 14.4 MHz. The fitted curve is the function as given in (1) with the only fitting parameter being $(\langle E^2(t) \rangle)^{0.5} = 137(2)$ V/cm. Precision studies are now underway to determine the exact value of the zero crossing and will be reported at the meeting.

Based on the initial results, it will be possible to determine an improved value for the polarizability difference $\Delta \alpha_o$ at a level that is better than a factor of 5 improvement over the best theoretical determination [3] and which can be used to improve the blackbody shift and total uncertainty to well below the 2×10^{-17} level. The stabilities of the two trap comparison have yielded values comparable to the expected stability limits. At averaging times of 100 s, a relative stability

Fig. 1. Observed difference between two $^{88}\text{Sr}^+$ standards as a function of operating trap frequency of the Paul trap system possessing micromotion. The fitted curve is a one-parameter fit using eq. (1).

between the two systems inferred a single trap stability of 7×10^{-16} which averaged down to 1×10^{-16} at 8,000 s.

A further improvement by a factor of 2 is expected when state preparation of the ground state is implemented [2].

IV. CONCLUSION

The experimental confirmation of micromotion shift cancellation together with improved knowledge of the polarizability difference of the ground and excited states of the S-D transition now allows the possibility for the $^{88}\text{Sr}^+$ ion system to achieve ultimate accuracies below the 10^{-17} level with stabilities that will allow access to accuracies in the 10^{-17} regime with a few hours of averaging.

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