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Absolute frequency measurement of the electric quadrupole transition of $^{88}Sr^+$

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***Abstract*—We report a new measurement of the 445 THz electric quadrupole transition of the strontium ion made using a GPS link to the SI second. Compared to our previous measurement reported in 2012, the operation of the optical clock has been improved in several ways, especially from a reduction of the micromotion shifts, of the black body radiation shift, and of the servo tracking errors. Moreover, the stability of the clock has been improved three-fold with state-preparation. The uncertainty of the optical clock during the measurement campaign was 7 mHz. The uncertainty of the frequency measurement was 0.75 Hz, limited primarily by the GPS link and to a lesser extent by the measurement statistics. The new frequency measurement is in good agreement with previously reported values.**

Keywords—absolute frequency measurement; single ion clock; optical atomic clock; GPS frequency link

I. Introduction

A number of optical clocks have achieved unprecedented low uncertainties and high frequency stabilities, significantly outperforming Cs fountain clocks that define the SI second [1]. For these reasons, and as further improvements continue to be made, optical atomic clocks are being considered for a re-definition of the SI second [2], [3]. Before this can be achieved, it is essential to measure their absolute frequencies with respect to the current definition of the SI second, and to demonstrate agreement over time and between laboratories. Toward this goal, we made a new absolute frequency measurement of the S–D transition of $^{88}Sr^+$ using a GPS link to the SI second. Brief descriptions of the $^{88}Sr^+$ ion clock operation and uncertainty evaluation are given in Section II. Details of the frequency measurement are presented in Section III.

II. Strontium ion optical clock

The optical clock developed at the National Research Council of Canada (NRC) is based on the $5s\,^2S_{1/2} - 4d\,^2D_{5/2}$ electric quadrupole transition of a trapped and laser-cooled single ion of $^{88}Sr^+$. The S–D transition is interrogated using an ultra-stable 674 nm laser system. The natural linewidth of the S–D transition is 0.4 Hz and its quality factor is $Q \simeq 10^{15}$. The ion is cooled on the strongly allowed $5s\,^2S_{1/2} - 5p\,^2P_{1/2}$ transition at 422 nm, with observed ion kinetic temperatures of typically 2 mK. A repump laser at 1092 nm is required to prevent decay of the $^2P_{1/2}$ state to the metastable $^2D_{3/2}$ state. An additional laser at 1033 nm is used to return the ion to the ground state once the ion state has been detected using the electron shelving method. The clock transition linecenter is determined by independently locking the probe laser to six resonances that connect to all the magnetic sublevels of the $^2D_{5/2}$ state. The lock is performed by cycling through the six resonances and the linecenter frequency is determined from the average of those frequencies. This Zeeman averaging method is used to cancel several shifts and to determine a virtual linecenter that is not affected by the linear Zeeman shift, the electric quadrupole shift (EQS), and the tensor Stark shifts. More details about the experimental setup and operation of the optical clock are given in [4]–[6].

Compared to the absolute frequency measurement reported previously [5], several improvements were implemented in the optical clock. The most important one, from a measurement perspective, was the implementation of a servo algorithm that continuously evaluates and tracks the cavity drift rate. Previously, a constant drift rate of typically 10 mHz/s was used in the servo system. Despite the low average drift rate of the reference ULE cavity, changes of only a few mHz/s yielded significant tracking errors that could only be partially corrected in post-processing [6]. The implemented servo algorithm evaluates the cavity drift rates using an exponential moving average of previously measured values. The tracking errors have been reduced by more than two orders of magnitude to 2×10^{-18} fractional uncertainty with this algorithm and do not necessitate post-processing of the frequency data [7].

Another significant improvement was the implementation of state-preparation that has decreased the instability of the lock to the ion linecenter by a factor of three, to 3×10^{-15} at 1-s averaging time [8]. As a consequence of the higher quantum jump rate, the cycle time through the resonances was reduced by a factor of four, with corresponding reductions of systematic shifts associated with the servo tracking errors and the cancellation of the electric quadrupole shift.

Another advance was a high-accuracy measurement of the differential static scalar polarizability, $\Delta\alpha_0$, of the clock transition [9]. Several benefits to the ion clock accuracy were obtained from a better knowledge of $\Delta\alpha_0$: a reduction of the blackbody radiation (BBR) shift uncertainty by a factor of two, a reduction of the micromotion shifts by a factor of more than 200, and a reduction of the thermal motion shifts by a factor of three [7].

The main sources of uncertainty during the frequency measurement reported here were the evaluation of the BBR shift and an uncertainty caused by acousto-optic modulator

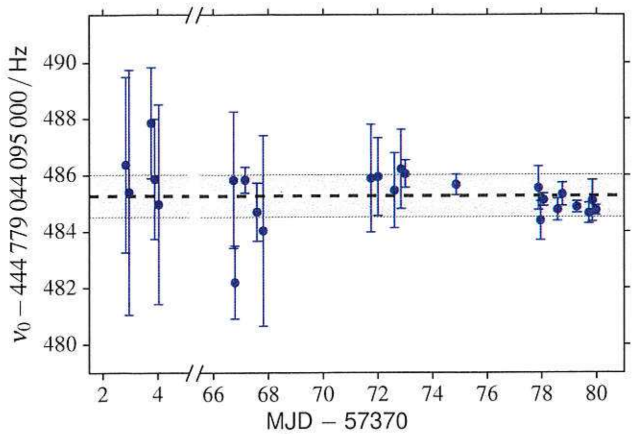

Fig. 1. Absolute frequency measurements of the S–D transition frequency of $^{88}Sr^+$ versus the modified Julian date (MJD). The data points are the results of individual measurement runs, with 1σ error bars determined from Allan deviation plots. The dashed line is the average ion frequency and the shaded area indicates the 0.75 Hz uncertainty of the measurement. Note that the determined frequency is not a simple average of the data shown. For more details see [7].

(AOM) frequency chirps. They each contributed approximately 1×10^{-17} to the uncertainty budget. All other shifts contributed 2×10^{-18} or less. The overall uncertainty of the ion clock frequency during the measurement campaign was evaluated at 1.5×10^{-17} in fractional units, which corresponds to 7 mHz at 445 THz.

III. Absolute Frequency Measurement

The frequency of the S–D transition of $^{88}Sr^+$ was measured by comparing the probe laser frequency to a reference maser using a fiber-based femto-second laser frequency comb [10]. The maser was itself calibrated using a GPS frequency link to the SI second [7]. The results were combined and corrected for various known shifts to determine the unperturbed ion frequency on the geoid. We have corrected for the offset of the GPS link from the SI second using the monthly BIPM Circular-T reports. The ion frequency was also corrected for the BBR shift, the light shift caused by the repumper laser, the thermal motion shift and the gravitational time-dilation shift. The corrected results are shown in Fig. 1. The measurement campaign resulted in more than 100 h of data.

The uncertainty of the measurement was dominated by the GPS link uncertainty evaluated at 0.67 Hz. The second most important contribution was from the 0.34 Hz statistical uncertainty caused by short-term maser frequency fluctuations and by the dead time in the operation of the optical standard and femto-comb laser link. The ion uncertainty contributed only 7 mHz. The ion frequency determined in the measurement campaign reported here is 444 779 044 095 485.27(75) Hz.

This result is in good agreement with previous results from our laboratory [4], [5] and from the National Physical Laboratories in the United Kingdom (NPL) [11], [12].

IV. Conclusion

We have reported a new measurement of the $^{88}Sr^+$ ion electric quadrupole transition at 445 THz. This measurement was obtained with several improvements made to the $^{88}Sr^+$ ion clock operation and accuracy. The measurement was made using a GPS link to the SI second and gave a new evaluation of the S–D frequency with an uncertainty of 0.75 Hz, or 1.7×10^{-15} in fractional frequency units. The result is in good agreement with previous measurements.

Future measurements at NRC will be performed using a state-of-the-art cesium fountain clock [13]. We expect to obtain a determination of the $^{88}Sr^+$ ion clock frequency with an uncertainty in the mid-10^{-16} level.

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