Quantum projection noise limited stability of a $^{88}$Sr$^+$ atomic clock

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Abstract. The evaluated accuracy of a single trapped $^{88}$Sr$^+$ ion clock referenced to the $5s^2S_{1/2} - 4d^2D_{5/2}$ transition at 445 THz at the National Research Council of Canada has reached $1.2 \times 10^{-17}$ over recent years. On the other hand, the stability of an atomic clock determines how long the signals from two similar clocks have to be compared to reach a given level of uncertainty. Here, we report on the improvement of the stability of NRC’s $^{88}$Sr$^+$ single ion clock by reducing the Allan deviation from $1 \times 10^{-14}$ to $3 \times 10^{-15}$ at 1 second averaging time. This is done by the implementation of a clear out laser that transfers the ion from the metastable state to the ground state at each cycle, followed by a state-preparation step that transfers the ion to the desired ground state magnetic sublevel of the probed transition.

1. Introduction

Optical atomic clocks based on single trapped ions have witnessed a dramatic development during the last few years [1-5]. At the National Research Council of Canada (NRC), we have developed an atomic clock referenced to the $5s^2S_{1/2} - 4d^2D_{5/2}$ transition of $^{88}$Sr$^+$ at 445 THz [3-5]. The evaluated fractional frequency uncertainty of the clock has reached $1.2 \times 10^{-17}$ by using several methods to reduce uncertainties. For example, the electric quadrupole shift and the tensor Stark shift are cancelled by probing several pairs of Zeeman components [6]. The micromotion shifts are reduced to the $10^{-19}$ level by minimizing ion micromotion and by using the accurately known value of the differential scalar polarizability of the clock transition, $\Delta \alpha_0$. This allows one to tune the trap frequency such that the time dilation and scalar Stark shifts cancel each other by a factor of about 200 [5]. Furthermore, the accurate knowledge of $\Delta \alpha_0$ has also reduced the uncertainty associated with the blackbody radiation shift [5].

It is crucial to optimize the clocks’ stability for the comparison of two similar clocks with such a low uncertainty level. Single-clock stabilities of $2-3 \times 10^{-16}/\sqrt{t}$ have been demonstrated with optical lattice clocks [7, 8]. However, the best stability of optical clocks based on a single trapped ion is about one order of magnitude larger due to the fact that the single atomic particle offers a significant smaller single-to-noise ratio to steer the local oscillator frequency [1, 9]. In this summary, we report on our recent improvement of the stability of our $^{88}$Sr$^+$ clock by reducing the Allan deviation from $1 \times 10^{-14}$ to $3 \times 10^{-15}$ at 1 second averaging time, comparable to the quantum projection noise limit for a 100 ms pulse [10]. The pulse sequence, state-preparation step, interrogation method, and stability measurement results are presented.
2. Experimental methods

2.1. The $^{88}$Sr$^+$ ion clock

Figure 1 shows the relevant energy levels of the $^{88}$Sr$^+$ ion. The $^{88}$Sr$^+$ ion is cooled using a frequency-stabilized diode laser at 422 nm that is red detuned by approximately a half-linewidth from the $5s\,^2S_{1/2} - 5p\,^2P_{1/2}$ line center. A repump laser at 1092 nm prevents the ion from decaying to the metastable $^2D_{5/2}$ state [11]. The average ion kinetic temperature observed reach es ~2 mK. The $S - D$ clock transition of the $^{88}$Sr$^+$ ion, having a natural linewidth of 0.4 Hz, is probed by an ultra-stable laser at 674 nm. A small magnetic field of 1~2 $\mu$T is applied to split the clock transition into ten resolved Zeeman components and to define the quantization axis for optical pumping. A “clear out” laser at 1033 nm is applied to return the ion from the $^2D_{5/2}$ metastable state to the ground state after excitation and before the next interrogation pulse. Usually, three symmetric pairs of Zeeman components are probed to determine cancellation of the first-order Zeeman shift, the electric-quadrupole shift, and other tensor shifts [4, 6]. The NRC $^{88}$Sr$^+$ reference ion is confined in an end-cap trap which is operated with a voltage amplitude of 212 V at a frequency of 14.408 MHz to reduce the micromotion shifts.

2.2. Pulse sequence and state-preparation

Figure 2 shows the pulse sequence used in the experiment. The total cycle time, $T_c$, is the sum of the probe pulse length, $T_p$, and the dead time, $T_d$. During the cooling pulse, the ion state is detected by monitoring the fluorescence at $S_1$. The clear out laser then transfers the ion from the metastable state $^2D_{5/2}$ to the ground state with an efficiency of essentially 100% even if the ion is found in the ground state at $S_1$. The fluorescence is monitored again at the end of the cooling stage, $S_2$, to verify that the clear out action was successful and that the ion was cooled for several ms.

State-preparation has been implemented in our current setup by optical pumping using circularly polarized 422 nm light. This assures the probe laser will interact with the ion placed in the ground state sub-level on every probe cycle since the $^{88}$Sr$^+$ ion has two ground state magnetic sublevels. A longitudinal Pockels cell followed by a quarter-wave plate provides a voltage-controlled wave plate on the 422 nm beam path. The voltage applied determines whether the polarization at the ion is linear, $\sigma^+$ or $\sigma^-$. State-preparation starts 2 ms before the 422 nm beam is turned off and lasts 2 ms longer to ensure that only circular polarized light interacts with the ion. Figure 3 shows the effect of using state-preparation with $\sigma^+$ light on the $S - D$ Zeeman spectrum with the ion found in the $m_J = +1/2$ sublevel 99% of the time.
Figure 2. (Colour online) Pulse sequence for one interrogation cycle. The 422 nm polarization is switched from linear to circular (±) for a duration of 4 ms, and starts about 2 ms before the end of the pulse [10].

Figure 3. (Colour online) Zeeman-resolved spectra of the $S - D$ transition of $^{88}\text{Sr}^+$ showing transition probability to the $^2D_{5/2}$ state, $p_m$, as a function of 674 nm laser detuning for the 422 nm light linearly (a) and $\sigma^+$ polarized during the last 2 ms of the pulse (b) [10].
2.3. Lock method

Experimentally, the line centers of the Zeeman components of the $S-D$ clock transition are probed at frequency offsets of $\pm \delta$ from line center to determine updated center frequencies [12-14]. The center frequency of the clock transition is the average of two symmetric Zeeman components (there is no first-order magnetic insensitive transition in the $^{88}$Sr$^+$ clock transition spectrum). This sequence is repeated for an averaging time $\tau$ to reduce the statistical uncertainty according to [10]

$$\sigma_y(\tau) = \frac{G}{\nu_0 \sqrt{1 - p_x^2}} \frac{T_c}{\tau}$$

where $\sigma_y$ is the standard Allan deviation, $G$ is a gain parameter, $p_x$ is the probability that the ion is in the metastable state after interaction with a probe pulse which is either blue or red detuned by $\delta$ with respect to the line center, and $T_c$ is the cycle time defined earlier.

The lock is usually operated by measuring the frequencies of six Zeeman components from three symmetric pairs that probe all the sublevels of the $^2D_{5/2}$ metastable state. This is because other important shifts can be canceled by averaging the frequencies of Zeeman pairs that connect to all of the $^2D_{5/2}$ state sublevels. These shifts include the linear Zeeman shift, electric quadrupole shift, and tensor Stark shift [4, 6].

Figure 4. (Colour online) Single-clock Allan deviation of $^{88}$Sr$^+$ ion as a function of averaging time, $\tau$, with and without state preparation [10].

3. Results

Figure 4 shows the single-clock Allan deviations as a function of averaging time. The result without state-preparation was obtained by comparing two $^{88}$Sr$^+$ ion optical frequency standards (an end-cap trap and a rf Paul trap with evaluated uncertainties of $1.2 \times 10^{-17}$ and $\sim 1 \times 10^{-16}$, respectively). The observed stability of $9 \times 10^{-15}/\sqrt{\tau}$ is in reasonable agreement with the calculated optimal stability without state preparation of $6.6 \times 10^{-15}/\sqrt{\tau}$.

For the result with the state-preparation, the stability measurements have been obtained by using self-comparisons in the end-cap trap. The probe laser frequency is locked to the $C_2$, $C_3$, and $C_4$ symmetric pairs as shown in Figure 3. Allan deviations can be calculated from all possible combinations, $C_2$ vs $C_3$, $C_2$ vs $C_4$, and $C_3$ vs $C_4$. The three Allan deviations from each run are averaged and the result divided by $\sqrt{6}$ to obtain the single-clock stability. The observed stability of $3 \times 10^{-15}/\sqrt{\tau}$ is in good agreement with the calculated quantum projection noise (QPN) limit of $2.3 \times 10^{-15}/\sqrt{\tau}$ with a probe pulse length of 118 ms [10]. This is one of the lowest instabilities reported
for a single trapped ion clock. Further improvement of the instability will necessitate better control of the probe laser frequency noise and of the background magnetic field noise.

4. Conclusions and outlook
We have presented improvements of the instability of our $^{88}\text{Sr}^+$ ion clock which now approaches the quantum projection noise limit. The improvements are made possible by introducing a clear out laser returning the ion back to the ground state after it is excited from the metastable state as well as an optical pumping step to put the ion into the desired ground state magnetic sublevel of the probed transition. The instability obtained is $3 \times 10^{-15}/\sqrt{\tau}$ which reduces the averaging time by an order of magnitude when averaging down to a certain accuracy compared to $1 \times 10^{-14}/\sqrt{\tau}$ when these two steps were not implemented.

The current accuracy of the NRC $^{88}\text{Sr}^+$ single ion clock is mainly limited by the uncertainty from the blackbody thermal field. In order to push down the uncertainty of the ion clock to the low $10^{-18}$ level, evaluation of the thermal field of the ion trap has been started recently. A test end-cap ion trap will be constructed and run under the normal operating conditions. The trap thermal field will be imaged by an IR camera to determine the temperatures of the ion trap parts. Combined with measurements of the emissivities of the various ion trap parts, the effective black body radiation field temperature at the ion will be determined by comparing the temperature measurement results with a finite element simulation [15].

A study of the gravitational red shift is planned by comparing the clock transition frequencies of $^{88}\text{Sr}^+$ ions trapped in rf Paul and end-cap traps [16]. A vertical translation stage with a displacement range of ~3 meters has been constructed. One of our ion clocks, the rf Paul trap, will be mounted on this translation stage and the comparison of the frequency between the two clocks will be able to precisely determine the relative gravitational red shift.

References
[1] Chou C W, Hume D B, Koelemeij J C J, Wineland D J and Rosenband T 2010 Phys. Rev. Lett. 104 070802
[2] Huntemann N, Okhapkin M, Lipphardt B, Weyers S, Tamm Chr and Peik E 2012 Phys. Rev. Lett. 108 090801
[3] Madej A A, Dubé P, Zhou Z, Bernard J E and Gertsvolf M 2012 Phys. Rev. Lett. 109 203002
[4] Dubé P, Madej A A, Zhou Z and Bernard J E 2013 Phys. Rev. A 87 023806
[5] Dubé P, Madej A A, Tibbo M and Bernard J E 2014 Phys. Rev. Lett. 112 173002
[6] Dubé P, Madej A A, Bernard J E, Marmet L, Boulanger J-S and Cundy S 2005 Phys. Rev. Lett. 95 033001
[7] Hinkley N, Sherman J A, Phillips N B, Schioppo M, Lemke N D, Beloy K, Pizzocaro M, Oates C W and Ludlow A D 2013 Science 341 1215
[8] Nicholson T L, Campbell S L, Hutson R B, Marti G E, Bloom B J, McNally R L, Zhang W, Barrett M D, Safronova M S, Strouse G F, Tew W L and Ye J 2015 Nat. Commun. 6 6896
[9] Rosenband T, Hume D B, Schmidt P O, Chow C W, Brusch A, Lorini L, Oskay W H, Drollinger R E, Fortier T M, Stalnaker J E, Diddams S A, Swann W C, Newbury N R, Itano W M, Wineland D J and Bergquist J C 2008 Science 319 1808
[10] Dubé P, Madej A A, Shiner A and Jian B 2015 Phys. Rev. A 92 042119
[11] Fordell T, Lindvall T, Dubé P, Madej, Wallin A E and Merimaa M 2015 Opt. Lett. 40 1822
[12] Bernard J E, Marmet L and Madej A A 1998 Opt. Commun. 150 170
[13] Riis E and Sinclair A G 2004 J. Phys. B: At. Mol. Opt. Phys. 37 4719
[14] Peik E, Schneider T and Tamm Chr 2006 J. Phys. B: At. Mol. Opt. Phys. 39 145
[15] Doležál M 2015 private communication
[16] Chou C W, Hume D B, Rosenband T and Wineland D J 2010 Science 329 1630