Special Topic: Precision Measurement Physics

The $^{40}\text{Ca}^+$ ion optical clock

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Ever since the mid-twentieth century, atomic clocks have become the most accurate time and frequency standards known. In 1967, the 13th CGPM (General Conference of Weights and Measures) decided to replace the definition of the second by ‘the duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the Cs-133 atom’. Optical atomic clocks are the next generation of atomic clocks with clock frequencies >10 000 times higher (100–1000 THz) and lie in the optical spectral range. Their accuracy could be 4 orders of magnitude better. Nowadays, the best optical atomic clocks have surpassed the best Cs fountain clocks by 2 orders of magnitude nowadays. Black squares represent the microwave clocks, red circles represent the optical clocks and blue stars represent the Ca$^+$ clock built in Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences (WIPM).

Among the different kinds of ion candidates, Ca$^+$ has its advantages: a simple laser system—all the lasers can be obtained by choosing diode lasers, optical frequency doubling not needed, quadrupole shift eliminated with a simple technique, existence of magic trapping the rf frequency for greatly suppressing the micromotion shifts, stably trapped at room temperature, etc. The research of optical clocks and quantum information based on Ca$^+$ is being carried all over the world. In recent years, the measurements of the Ca$^+$ clock transition frequency have been made by Innsbruck University in Austria, NICT of Japan and Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences (WIPM).

The Ca$^+$-clock research in WIPM has been going on for more than two decades. Single Ca$^+$ is trapped in the Paul traps and then laser cooled, successfully locked to the 729-nm probe laser to an ultra-stable cavity with a fineness of >200 000 afterwards. The probe laser has been locked to the ion transitions. There are a variety of potential sources of systematic shift that might be associated with the Ca$^+$ clock; the systematic effects should be considered generally to include the Doppler and Stark shifts caused by both the micromotion and the secular motion, the blackbody radiation Stark shift, the Zeeman shift, ac Stark shift (light shift), quadrupole shift, etc. The linear Zeeman shift, the quadrupole shift and the tensor...
part of the Stark shift would be canceled out by averaging six spectral-line frequencies.

Like most ion-based clocks, the micromotion shifts are one of the dominant systematic-uncertainty sources, which can be as large as $10^{-15} \sim 10^{-13}$ if not carefully compensated. At WIPM, the micromotion shifts were minimized and evaluated using the rf-photon correlation technique and the observation of the ion imaged on a CCD camera [7]. Recently, new vacuum chambers have been built and one can probe the micromotion sidebands in three dimensions; this method is much more accurate. By keeping the ion trapped at the ‘magic’ rf trapping field at $\sim 24.8$ MHz, the micromotion-shifts uncertainty can be easily suppressed to $<1 \times 10^{-18}$ [8].

Another important systematic shift is called the blackbody radiation shift. This shift is well known and can be precisely calculated if one knows the exact environmental temperature sensed by the ion and the related atomic constant: the static differential polarizability. This constant is difficult to calculate with very high precision, but it can be indirectly measured by measuring the ‘magic’ rf trapping frequency. The ‘magic’ rf trapping frequency is precisely measured with $\sim 2$ orders of magnitude better precision than the calculations; the blackbody radiation shift due to atomic constant uncertainty is then reduced to $<1 \times 10^{-18}$ for a room-temperature-based Ca$^+$ clock [8].

With further improvements made to reduce the servo error, the uncertainty of the evaluation of the systematic shifts has achieved a level of $2.0 \times 10^{-17}$ (Table 1), currently limited by the blackbody radiation field evaluation uncertainty of 1.6 K.

| Contribution                          | Fractional frequency shift | Fractional frequency uncertainty |
|---------------------------------------|----------------------------|----------------------------------|
| BBR field evaluation (temperature)    | 863                        | 19                               |
| BBR coefficient ($\Delta \alpha_B$)    | 0                          | 0.3                              |
| Excess micromotion                    | 0                          | 0.4                              |
| Second-order Doppler (thermal)        | $-5.0$                     | 2.5                              |
| ac Stark shift                        | 1.2                        | 1.3                              |
| Residual quadrupole                   | 0                          | 2.3                              |
| Zeeman effect                         | 0                          | 1.5                              |
| Servo                                 | 0.0                        | 3.0                              |
| Total                                 | 859                        | 20                               |

Besides uncertainty, stability is also important for clocks. In recent years, WIPM has introduced the state preparation technique—a faster and more efficient control system is implemented; Ramsey interrogation is also introduced, making the clock stability approximately four times better than in the year 2016 [7]. A frequency comparison between two clocks shows that the stability of each single clock has reached $7 \times 10^{-18}$ in $\sim 500000$ s of averaging time (Fig. 2).

Ca$^+$ is also a candidate for secondary representation of the SI second. In the years 2012, 2015 and 2017, the measurement results of WIPM, NICT and Innsbruck University were adopted by CIPM and the recommended frequency of the Ca$^+$-clock transition has been revised three times. The uncertainty of the recommended value is reduced from $4 \times 10^{-14}$ to $2.4 \times 10^{-15}$ [Consultative Committee for Time and Frequency (CCTF) Reports-19 (2012), 20 (2015) and 21 (2017)].

In the future, further study on the evaluation of the BBR field is required and we are now working on housing the ion trap in a liquid-nitrogen-temperature environment to obtain further reductions in the BBR-shift uncertainty. With reductions in the shifts and their uncertainties mentioned above, a $^{40}$Ca$^+$-ion clock with an uncertainty at the $10^{-18}$ level can be achieved. Furthermore, the stability is still $\sim 10$ times worse than the quantum projection noise (QPN) limit of the single Ca$^+$ clock, mainly limited by our clock-laser stability of $8 \times 10^{-16}$. Clock lasers with a stability of $<3 \times 10^{-16}$ at $1\sim 300$ s are needed to reach the QPN limit. To further improve the ion-clock stability, one has to build a clock referenced to multiple ions. Optical trapping of the ions under the magic wavelength would be one of the options [9]. Like the PTB portable Sr clock [10], one of the WIPM Ca$^+$ clocks has been moved to a container that can be easily moved by a truck. A comparison experiment is in progress. Thanks to their simplicity, it might be easier to make portable Ca$^+$-clocks—even space ones. Hopefully, in the near future, highly accurate and portable Ca$^+$ clocks will find applications in mapping Earth’s gravitational potential, testing fundamental physics and navigation.

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Frequency can be measured much more precisely than any other physical quantity, and much of precision metrology depends critically on the measurement of frequency and its inverse, time-interval. Optical electromagnetic waves (or ‘light’), oscillating at more than 10^{14} per second, are at least 1000 times more precise for time/length measurement compared to microwave frequencies near 1 GHz. However, electronics do not respond to such rapid optical oscillations. Thus, optical frequencies cannot be measured directly, and must be divided down to the radiofrequency (RF) regime for electronic counting. It has been a historical challenge to realize optical frequency division with arbitrary divisors.

In the 1970s, the absolute frequency of a methane-stabilized He-Ne laser was measured by dividing its frequency to the RF region with a frequency chain based on many nonlinear frequency conversions. By measuring the laser frequency, the measurement accuracy of the velocity of light was improved 100 times [1]. However, the frequency chain for optical frequency division was complex and huge in size, and covered only a few specific wavelengths. The accuracy of the frequency chain was only 10^{-10}, limiting its application in precision measurements with high accuracy.

Optical frequency combs, invented in 1999, have revolutionized the art of optical frequency division [2,3]. The spectrum of an optical frequency comb consists of a series of discrete optical frequency lines uniformly spaced by a RF interval. Using the comb to interfere with optical waves, researchers can link optical-optical and optical-microwave frequencies in a single step. In 2001, the first frequency comparison between a Ca optical clock and a Hg^{197} optical clock was made using an optical frequency comb [4]. In 2004, an international frequency comparison of four combs (two different types) from three laboratories verified that optical frequency combs could support optical frequency division with 10^{-19} uncertainty [5], confirming that combs can serve as the clockwork for optical atomic clocks with 10^{-18} uncertainty. Development of optical atomic clocks bloomed in the following 15 years: both the fractional frequency instability (long term) and uncertainty of optical clocks reached 10^{-18}, and progress is being made towards 10^{-18}−10^{-20} [6].

In most early work, the noise from combs, RF electronic timebases and other technical noise limited the division uncertainty to the 10^{-19} level. In 2015, most of the noise from combs and RF timebases was reduced using a transfer oscillator scheme [7,8] and synchronously counting relative to a H-maser. With these techniques of noise reduction, the frequency ratio of two independent frequency-stabilized lasers was simultaneously and independently measured with a Ti:sapphire comb and a fiber comb, and the agreement between these frequency ratio measurements was 3 × 10^{-21} [8]. In 2016, the comb frequency noise was further reduced by employing the transfer oscillator scheme and a narrow-linewidth, frequency-stabilized comb. Meanwhile, a self-referenced RF timebase divided from one of the laser frequencies was introduced to remove the noise from an additional RF timebase.