# Trapped-ion optical atomic clocks at the quantum limits

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**BIOGRAPHIES**

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David J. Wineland received a BA degree from the University of California, Berkeley in 1965 and a Ph.D. from Harvard University in 1970. He has been a member of the Time and Frequency Division of the National Institute of Standards and Technology (NIST) in Boulder, Colorado since 1975, where he is a group leader and NIST Fellow. David's primary research interests are precision spectroscopy, atomic clocks, quantum information, and quantum-limited measurements.

## ABSTRACT

Frequency and its inverse, time, are the most accurately measured quantities. Historically, improvements in the accuracy of clocks have enabled advances in navigation, communication, and science. Since 1967, the definition of the International System (SI) second has been based on the frequency of a microwave transition in cesium, and present day cesium atomic clocks have a fractional uncertainty near $10^{-16}$. Recently, a new type of atomic clock based on optical transitions has been developed, with a current fractional uncertainty near $10^{-18}$ (approximately one second divided by the age of the universe), and they are rapidly improving.

This talk presents a brief summary of the development of optical atomic clocks, with a focus on the $Al^+$ quantum-logic clock developed at NIST. We discuss the current state-of-the-art in optical clock performance, and describe new applications in sensing and fundamental physics. Future directions in optical atomic clock research are also considered.


## INTRODUCTION

Taking advantage of advances in low noise optical local oscillators [1] and optical frequency measurements [2, 3], optical atomic clocks [4] have surpassed the performance of the cesium microwave atomic clocks upon which the SI second is based, and they are on the cusp of transitioning from scientific experiments to workhorse tools for metrology and fundamental physics. These clocks are based on optical transitions in trapped and laser cooled atoms or ions and they derive their performance advantages from high transition frequencies, narrow transition linewidths, and small systematic frequency shifts. State-of-the-art optical atomic clocks are now reaching fractional frequency instabilities of $6 \times 10^{-17}\ \tau^{-1/2}$, where $\tau$ is the measurement duration [5], and systematic uncertainties of $2 \times 10^{-18}$ [6]. In addition to the possibility of a redefinition of the SI second based on optical atomic clocks [7], optical clocks may also find applications ranging from advanced navigation systems and relativistic geodesy to tests of fundamental physics [8, 9].

## ALUMINUM ION QUANTUM-LOGIC CLOCKS

The 267 nm $^1S_0 \leftrightarrow {}^3P_0$ transition of $Al^+$ was recognized as a promising atomic transition for optical clocks as early as 1982 [10] because of its small transition linewidth (8 mHz [11]), its insensitivity to magnetic fields and electric field gradients, and later its small blackbody radiation shift ($3.8 \times 10^{-18}$ at 300 K [12]). However, due to the inaccessibility of its internal transitions for laser cooling and state detection, $Al^+$ did not become a practical choice for clocks until the development of quantum-logic spectroscopy [13]. In quantum-logic spectroscopy, one spectroscopy ion (e.g., $Al^+$) and one logic ion (e.g., $Be^+$, $Mg^+$, or $Ca^+$) are trapped together in a linear radio frequency (RF) Paul trap. Because the two ions are strongly coupled by their mutual Coulomb interaction, laser cooling of the logic ion sympathetically cools the motion of the spectroscopy ion, and a two ion logic gate can be used to transfer the state of the spectroscopy ion onto the logic ion, thus eliminating the need for laser cooling and state detection transitions in the spectroscopy ion. These techniques were used to demonstrate the first $Al^+$ quantum-logic clock at NIST in 2008, with $Be^+$ used as the logic ion [8].

A second-generation NIST $Al^+$ quantum-logic clock was constructed using $Mg^+$ as the logic ion, which reached a systematic uncertainty of $8.6 \times 10^{-18}$ [14]. The dominant contributions to the systematic uncertainty were motional time dilation shifts. The motion of ions trapped in RF Paul traps can be divided into two components: motion driven by the RF electric field of the ion trap due to trapping field imperfections, which we call excess micromotion, and thermal motion plus the associated motion driven by the RF electric field of the ion trap assuming ideal trapping fields, which we call secular motion. The contributions to the second-generation clock systematic uncertainty due to excess micromotion and secular motion were $6 \times 10^{-18}$ and $5 \times 10^{-18}$, respectively. The stability of the clock was limited by quantum projection noise at $2.0 \times 10^{-15}\ \tau^{-1/2}$. In addition to NIST, $Al^+$ quantum-logic clocks are also under development at Physikalisch-Technische Bundesanstalt (PTB), Germany; University of Innsbruck, Austria; and Wuhan Institute of Physics and Mathematics, China.

The first and second generation NIST $Al^+$ quantum-logic clocks were used to demonstrate some of the potential applications of optical atomic clocks. The first generation $Al^+$ clock was compared with an optical clock based on $Hg^+$ with a frequency ratio measurement uncertainty of $5 \times 10^{-17}$, and the stability of the measured frequency ratio was used to constrain a possible time variation of the fine structure constant [8]. The first and second generation $Al^+$ clocks were compared and their frequency difference was found to be smaller than the systematic uncertainty of the first-generation clock ($2.3 \times 10^{-17}$) [14]. To demonstrate the potential of optical atomic clocks for relativistic geodesy, the second generation $Al^+$ clock was raised by 33 cm and the resulting gravitational time dilation shift was measured [15].

## MOTIONAL TIME DILATION SHIFTS

Currently, a third-generation NIST $Al^+$ quantum-logic clock is under development with the goal of reduced systematic uncertainty due to motional time dilation shifts [16]. As in the second-generation clock, $Mg^+$ is used as the logic ion. In previous $Al^+$ clocks, rapid anomalous heating of the ions' secular motion [17] necessitated performing continuous Doppler laser cooling during the clock interrogation to minimize the secular motion time dilation shift. At the Doppler cooling temperature limit (≈1 mK for $Mg^+$), precise measurement of the temperature is challenging. In the second-generation $Al^+$ clock, the secular motion time dilation shift of $-16.3 \times 10^{-18}$ was evaluated with a 30 % uncertainty [14]. To reduce both the magnitude of the shift and its uncertainty, the third-generation $Al^+$ clock is operated with the ions' secular motion initially cooled to near the quantum mechanical ground state (≈10 μK). To make this possible, we have replaced the second-generation ion trap with a new design that exhibits motional heating rates two orders of magnitude lower than previous $Al^+$ clock ion traps. The ions' motion is cooled before the clock interrogation using Raman sideband cooling on $Mg^+$, and because of the low heating rates no further cooling is required during the clock interrogation. The resulting secular motion time dilation shift of $(-1.9 \pm 0.1) \times 10^{-18}$ is dominated by the quantum mechanical zero point energy of the ions' motion, and its uncertainty is a factor of 50 lower than that of the second-generation clock [16].

Excess micromotion is caused by imperfections of the ion trap RF and DC electric fields. Efforts are currently underway at NIST to suppress RF electric field imperfections by careful design of the ion trap electrode geometries and by applying RF potentials to compensation electrodes. The DC electric field imperfections are suppressed by using ion trap loading methods that minimize charging of nearby dielectric surfaces (such as ablation and photoionization [18]) and by applying DC potentials to compensation electrodes, thereby reducing the magnitude of the micromotion time dilation shift. Other groups have built ion traps with electric fields sufficiently close to ideal to reduce the magnitude of the excess micromotion time dilation shift below $10^{-19}$ [19].

## CLOCK COMPARISON MEASUREMENT STABILITY

All atomic clocks are fundamentally limited in stability by quantum projection noise [20], which is a result of the probabilistic nature of measurements in quantum mechanics. For Ramsey spectroscopy of unentangled atoms, this limit is called the standard quantum limit and is given by $(2\,\pi\,\nu)^{-1}\,(N\,T\,\tau)^{-1/2}$, where $\nu$ is the atomic transition frequency, $N$ is the number of atoms, and $T$ is the Ramsey free-precession or interrogation time. The interrogation time is typically limited by the coherence time of the local oscillator at about 0.1 s to 1 s. Thus, most efforts to improve trapped-ion optical clock stability focus on increasing the number of ions [19, 21] or improvements to the local oscillator stability [22].

An alternative path to improved clock stability is to devise optical clock protocols in which the interrogation time is not limited by the local oscillator coherence time, but instead is limited only by the atomic coherence time. The atomic coherence time for $Al^+$ is limited by the 20.6 s excited state lifetime [11]; some optical clock species have excited state lifetimes that are significantly longer. One protocol aims to measure the frequency difference of two clocks by probing both clocks using phase locked local oscillators and using the correlations in the transition probabilities of the two clocks as the measurement signal [23, 24, 25]. This protocol was demonstrated experimentally for a comparison of two $Al^+$ ions in the same ion trap with a clock comparison fractional frequency instability of $3.7 \times 10^{-16}\,\tau^{-1/2}$ at a probe time of 3 s, which is an order of magnitude longer than that supported by the local oscillator coherence [26]. While this protocol only reduces the instability of a comparison of two clocks, an alternative protocol has been proposed which would reduce the instability of a single clock, based on using multiple atomic ensembles to extract more information about the local oscillator phase noise [27].

## CONCLUSION

The future is bright for optical atomic clocks. Both trapped ion and optical lattice clocks are rapidly reducing their systematic uncertainties, and no fundamental limits to further improvement have been reached. Optical lattice clocks have recently reached their quantum projection noise instability limit [28]. The relatively higher quantum projection noise limit of trapped ion clocks was reached several years ago, and now efforts are underway to increase the number of ions [19, 21], to improve the local oscillator stability [22], and to implement protocols that allow longer interrogation times [25]. While the majority of optical clocks are still complex laboratory research projects, some optical clocks are now capable of being

transported [29] and operating with high fractional uptime [30]. Optical atomic clocks are already the most precise measurement tools of any kind, and as their performance continues to improve, it is likely that unforeseen new applications will become possible.

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