NEWS & VIEWS

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**ATOMIC CLOCKS**

# Accurate and stable timekeeping

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Atomic clocks reached a record-breaking uncertainty of less than $10^{-18}$ and the time needed to compare clocks is now less than an hour. These results push towards a possible redefinition of the second from a microwave to an optical standard.

*Refers to* Brewer, S. M. et al. $^{27}Al^{+}$ quantum-logic clock with a systematic uncertainty below $10^{-18}$. *Phys. Rev. Lett.* **123**, 033201 (2019) | Oelker E. et al. Demonstration of $4.8 \times 10^{-17}$ stability at 1s for two independent optical clocks. *Nat. Photon.* https://doi.org/10.1038/s41566-019-0493-4 (2019).

There are two aspects that any precision measurement must address: systematic errors and statistical uncertainties. Two groups report advances on both these fronts[1,2]. Writing in *Physical Review Letters*, Samuel Brewer and co-workers report progress in characterizing and reducing systematic errors for the aluminium ion clock operated by the principal USA metrological laboratory — the National Institute of Standards and Technology (NIST) in Boulder, Colorado[1]. The NIST Al clock is now the world's most accurate timepiece, guaranteed to neither gain nor lose 400 ms over the age of the Universe[1]. As for statistical uncertainty, writing in *Nature Photonics*, Eric Oelker and co-workers report a parallel advance in faster averaging of the noise inherent to atomic clocks[2].

Measuring time requires observation of a stable periodic process. The elapsed time is simply a product of the number of counted periods and the duration of each period. I will refer to this simple, yet fundamental, equation as the timekeeper's formula. A grandfather clock is a mechanical realization of the timekeeper's formula — each swing of the pendulum is counted by the escapement mechanism, which converts the pendulum motion into circular motion that advances the clock's hands. Optical atomic clocks (pictured) realize the same formula in a rather different way. An atomic transition is resonantly excited by a tuneable laser. Once the laser is tuned to the atomic transition frequency, the timekeeper's formula applies: the oscillations of the laser electromagnetic wave are counted at the source, and the atomic transition frequency determines the period.

The appearance of an atom is far from being cameo in such clocks. Laser cavities and therefore laser frequencies drift over time, whereas atomic frequencies do not. Also, because atoms are universal and identical objects, it is guaranteed that atomic clocks at different locations measure the flow of time in the same fashion. This is a powerful idea and over the past half-century, precision time-keeping has been carried out with atomic clocks.

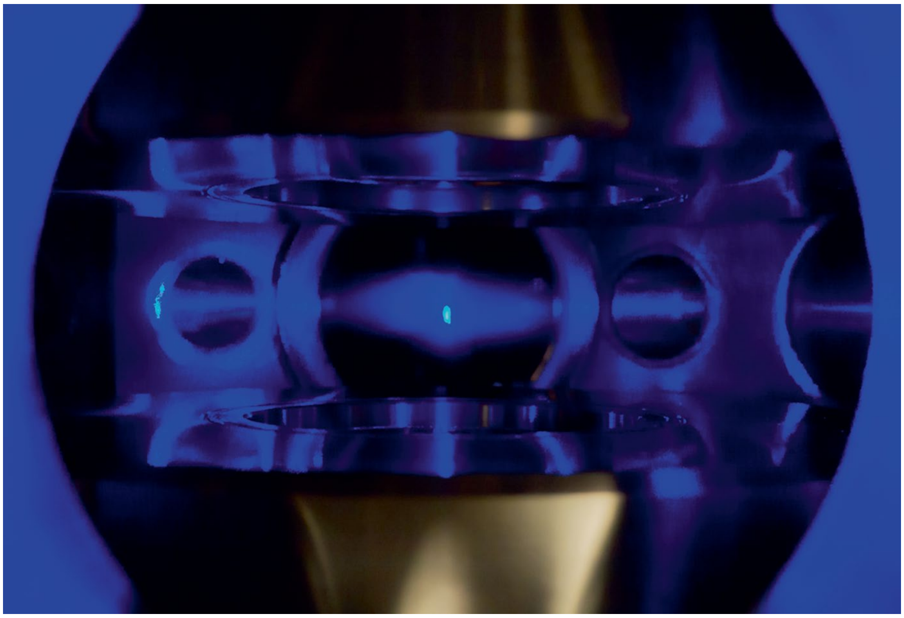
There are two challenges in implementing an atomic clock. The first is to make sure that the quantum oscillator (atom) is well protected from external perturbations. This is where the NIST aluminium ion clock has excelled. Brewer et al. have determined the frequency of the $Al^{+}$ transition to 18 significant figures ($9.5 \times 10^{-19}$ fractional uncertainty) by carefully evaluating the effects of numerous perturbations in their clock.

Another challenge is the process of tuning (locking) the laser to the atomic transition frequency. Because the measurement process is inherently noisy, locking requires averaging over repeated measurements. The averaging error scales down as the inverse square root of the number of measurements, or as $1/\sqrt{\tau}$ for a total integration time $\tau$. For example, in $Al^{+}$ the reported fractional averaging uncertainty or stability is $1.2 \times 10^{-15}/\sqrt{\tau}$, where $\tau$ is in seconds. This means that reaching a fractional uncertainty of $10^{-18}$ requires a 2-week experimental campaign.

This brings us to the important advance in stability announced by Oelker et al. This collaboration demonstrated averaging to a fraction of $10^{-18}$ in 1 hour. What is the reason for such an apparent disparity in integration times for the two experiments?

The primary reason for the disparity is that the $Al^{+}$ clock uses a single ion, whereas Oelker et al. have employed another class of atomic clock: optical lattice clocks[3], which allow simultaneous probing of an ensemble of thousands of strontium atoms. In other words, optical lattice clocks enable thousands of single quantum oscillator experiments to be run in parallel.

The most fundamental source of noise in both experiments is the projective nature of



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a quantum measurement. Initially, the atoms are in the ground state; a laser pulse then drives the initial state into a coherent superposition of the ground and excited states. The resulting excited state population depends on the difference (detuning) between the laser and atomic frequencies. Determination of the population is subject to quantum mechanical uncertainty inherent to projective measurements. To paraphrase Einstein, God does play dice, but the die is loaded, weighted by the laser detuning. Repeated measurements are needed to infer that weight and thus the detuning of the clock laser. In optical lattice clocks the projective measurements are carried out simultaneously on many atoms, drastically enhancing the rate of inference.

Another source of noise in atomic timekeeping is the noise of the laser cavity. To reduce this technical noise, Oelker et al. used a new cryogenically cooled silicon laser cavity. This design reduces Brownian noise in cavity mirrors and produces light that remains perfectly harmonic (coherent) over nearly a minute.

Atomic clocks are arguably the most accurate instruments ever built. Why would one care about even more accurate clocks? First, pushing quantum technology to its limits can have far-reaching implications. For example, ion clocks such as $Al^+$ served as a platform for pioneering demonstrations of quantum information processing. In fact, the $Al^+$ clock uses quantum logic gate for the population readout. Second, if the conventional physics perturbations, such as the influence of stray electrical fields and black-body radiation, are well characterized and controlled, atomic clocks can be used to search for exotic physics, such as gravitational waves, dark matter or variation of fundamental constants[4].

Measuring more quickly and to exquisite levels of accuracy has indisputable merits too. Of course, waiting for months to get a single measurement is an exercise in patience and speeding things up frees time. In particular, it means that the evaluation of the systematic errors can be performed more quickly. Moreover, exotic physics signals, such as from gravitational waves or lumpy dark matter, come as short transients. Therefore, better clock stability translates into a broader discovery reach.

Finally, the SI unit of time, the second, is defined in terms of the output of an atomic clock based on microwave transition in caesium-133 atoms. Currently, optical clocks[5] with their substantially higher frequencies have outperformed the microwave Cs standard by two orders of magnitude in accuracy. The reported advances in atomic timekeeping are anticipated to lead to an eventual redefinition of the SI second.

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