Gauging the Temperature Sensitivity of a Nuclear Clock

Researchers have characterized the temperature-induced frequency shifts of a thorium-229 nuclear transition—an important step in establishing thorium clocks as next-generation frequency standards.

By **Davide Calonico**

Atomic clocks are at the core of many scientific and technological applications, including spectroscopy, radioastronomy, and global navigation satellite systems. Today's most precise devices—based on electronic transitions in atoms—would gain or lose less than 1 second over the age of the Universe. An even more accurate timekeeping approach has recently emerged, based on a clock ticking at the frequency of a nuclear transition of the isotope thorium-229 (^{229}Th) [**1**, **2**]. Now a collaboration between the teams of Jun Ye of JILA, the National Institute of Standards and Technology, and the University of Colorado Boulder and of Thorsten Schumm of the Vienna Center for Quantum Science and Technology has characterized one of the main sources of the systematic uncertainties that might spoil a clock's accuracy: temperature-induced shifts of the clock transition frequency [**3**]. The characterization of the four strongest transitions of ^{229}Th allowed the researchers to identify the transition with the smallest temperature sensitivity.

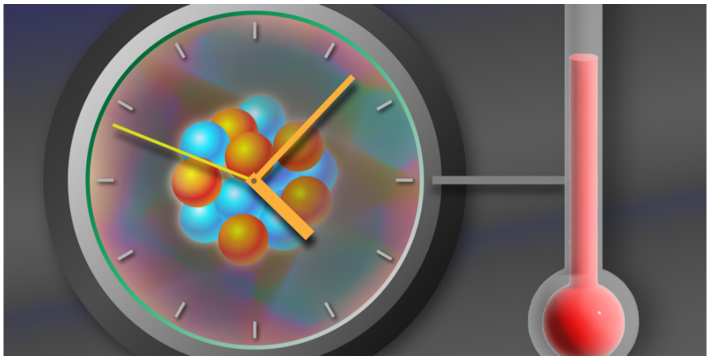

Figure 1: Researchers have characterized the temperature dependence of nuclear transitions of thorium-229—a promising system for building ultraprecise, miniaturized nuclear clocks.
Credit: APS/**Alan Stonebraker**

During the long journey that led to modern atomic clocks, researchers overcame two main challenges. First, they constantly worked to improve figures of merit such as the stability and accuracy of the atomic clock [**4**]. Second, they strove to miniaturize such clocks [**5**], seeking to build compact devices that can be embedded in instrumentation or placed onboard satellites. Present atomic clocks have achieved an outstanding frequency accuracy—at the level one part in 10^{+18}, paving the way to a redefinition of the unit of time in the International System of Units [**6**]. But these state-of-the-art clocks are complex and bulky setups, requiring several lasers for cooling, as well as ultra-high-vacuum and cryogenic cooling technologies.

An ultraprecise clock that is smaller and simpler would be a paradigm shift—and nuclear clocks offer a route toward that goal (Fig. **1**). In 2024, a collaboration involving the Vienna group observed for the first time a promising nuclear transition at vacuum-ultraviolet (UV) wavelengths in thorium isotopes [**4**]. Immediately thereafter, a collaboration involving both the Colorado and Vienna groups took further steps toward building a nuclear clock by characterizing that transition with high precision and by linking the transition frequency to an optical atomic clock [**2**]. The thorium transition has unique features: It is a nuclear, rather than electronic, transition, but occurs at very low energy, meaning that it can be excited using lasers at UV wavelengths—for which technology is much more mature and available than for x-ray or gamma-ray wavelengths. After about

75 years of atomic clocks, the shift from electronic to nuclear transition would be a monumental change of perspective [**7**].

Another interesting feature of the nuclear transition is the fact that, compared to an electronic transition, it's more shielded from interactions with environmental electromagnetic disturbances—a great asset for engineering an accurate clock. This shielding also screens the transition from interactions with electrons of surrounding atoms. As a result, one can conceive a solid-state device in which thorium atoms are placed into a crystal matrix. Such a possibility means that vacuum technology, laser cooling, and cryocooling may no longer be required—a potentially dramatic simplification that could lead to a miniaturized clock with unparalleled metrological applications.

But a lot remains to be done before a viable nuclear clock is established. In the new work, Ye, Schumm, and their collaborators start to dig deeper into the real possibilities of a thorium clock and into the factors that affect clock accuracy. In particular, the researchers perform a comprehensive analysis of the temperature shifts of the transition frequencies, which are caused by the interaction of blackbody radiation from the environment with the nucleus and the electrons around it.

Mitigating blackbody-radiation shifts has always been an important challenge for atomic clocks. For cesium clocks, which have been used since 1967 in the official definition of the second, the problem of environmental blackbody radiation was addressed only in 1982 [**8**]. It took 15 years for the clocks to achieve the precision required to correct for blackbody-radiation shifts. Ever since, the correction of temperature effects became a strict requirement for high-accuracy clocks used as primary frequency standards. The determination of blackbody-shift corrections remains a challenging task, both for theoretical and experimental reasons [**9**].

Optical clocks based on ytterbium, strontium, mercury, and aluminum offer a temperature sensitivity 10 times smaller than those based on cesium. What about thorium? Ye's and Schumm's teams investigate the temperature sensitivity of thorium in a solid-state matrix, characterizing it in the same crystal for the four strongest transitions of ^{229}Th. Their work delivers interesting physical insights into the physics of temperature-induced shifts. In particular, they focus on the energy structure of ^{229}Th, whose electric quadrupolar moment causes the ground and excited isomer states to split into four magnetic-dipole-allowed transitions. The resulting energy structure is sensitive both to temperature and to the electric-field gradient, which shift the two lowest-energy transitions and the two highest-energy transitions in opposite directions. At the same time, temperature-induced changes of the electron density at the nucleus induce same-direction shifts of all lines. Observing both the frequencies of the unsplit transitions and those of the split transitions, the teams gain deep insights into interesting nuclear dynamics, revealing how temperature affects electron density, electric-field gradient, and the field-gradient asymmetry at the nucleus.

Most importantly, the results enable the teams to pinpoint one of the measured transitions as the most promising candidate for a future solid-state thorium-based clock. The transition's temperature sensitivity of 0.4 kHz/K means that a crystal-temperature stability of 5 μK—which is practically achievable—would be sufficient to reach a fractional frequency precision of 10^{-18}. Further work on this scheme will need to address whether the clock accuracy may also be limited by other kinds of interactions between the thorium and its solid-state host.

This work is clearly not the last word in thorium-based nuclear clocks. In fact, thorium atoms can also be confined in electromagnetic ion traps—a scheme that would allow detailed studies of the factors contributing to temperature shifts by removing the complexities and imperfections inherent in a solid-state environment. Many more studies will be needed to determine whether thorium clocks can truly fulfill their promise. But we are just at the start of an exciting and rapidly evolving metrological journey.

Davide Calonico: National Institute for Metrological Research (INRIM), Turin, Italy

REFERENCES

1. J. Tiedau *et al.*, "Laser excitation of the Th-229 nucleus," **Phys. Rev. Lett. 132, 182501 (2024).**
2. C. Zhang *et al.*, "Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock," **Nature 633, 63 (2024).**
3. J. S. Higgins *et al.*, "Temperature sensitivity of a thorium-229

solid-state nuclear clock," **Phys. Rev. Lett. 134, 113801 (2025).**

4. H. Katori, "Optical lattice clocks and quantum metrology," **Nat. Photonics 5, 203 (2011).**
5. Z. L. Newman *et al.*, "Architecture for the photonic integration of an optical atomic clock," **Optica 6, 680 (2019).**
6. N Dimarcq *et al.*, "Roadmap towards the redefinition of the second," **Metrologia 61, 012001 (2024).**
7. K. Beeks *et al.*, "The thorium-229 low-energy isomer and the nuclear clock," **Nat. Rev. Phys. 3, 238 (2021).**
8. W. M. Itano *et al.*, "Shift of $^2S_{1/2}$ hyperfine splittings due to blackbody radiation," **Phys. Rev. A 25, 1233 (1982).**
9. S. R. Jefferts *et al.*, "High-accuracy measurement of the blackbody radiation frequency shift of the ground-state hyperfine transition in ^{133}Cs," **Phys. Rev. Lett. 112, 050801 (2014).**