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News & Highlights

Breakthrough Science Portends Nuclear Clocks of Unprecedented Precision

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In a series of three papers published in 2024 [1–3], physicists in Austria, Germany, and the United States reported the first direct observations with table-top lasers of a new nuclear process, in which the nucleus of a thorium atom absorbs a photon and goes into an excited state, then re-emits the photon and returns to its ground state. This "thorescence" phenomenon "is exactly the same process as fluorescence, but it takes place inside the nucleus," said Ekkehard Peik, professor and head of the department of time and frequency at the Physikalisch-Technische Bundesanstalt (the German national metrology institute) in Braunschweig, Germany.

In early 2024, Peik's research group reported that they could stimulate thorium with an ultraviolet (UV) laser and gave a rough estimate of the frequency of the emitted light [1]. The same process was confirmed by Eric Hudson, professor of physics and astronomy, and his research group at the University of California, LA, USA, using a different crystalline material [2]. Just two months later, Jun Ye, professor of physics, and his team at Joint Institute for Laboratory Astrophysics (JILA, a facility managed collaboratively by the US National Institute of Standards and Technology and the University of Colorado) in Boulder, CO, USA, improved the spectral resolution by five orders of magnitude, a spectacular increase in accuracy [3,4]. This work of Ye and colleagues clears the way for the development of a "nuclear clock," which would potentially be more accurate, more stable, and more portable than the atomic clocks that have been the state of the art for more than 50 years.

While atomic clocks are sensitive enough to detect effects like time dilation and to keep the Global Positioning System working, a nuclear clock might be sensitive to new physics [5]. Detections of dark matter? Variations in the fine-structure constant? Violations of Einstein's equivalence principle? All possible, though speculative to varying degrees. "In just a few years, you could accomplish progress that would take atomic clocks decades to achieve," said Victor Flambaum, a professor of physics at the University of New South Wales (Sydney, NSW, Australia) who has written several papers on potential "new physics" that could be uncovered by the new clocks.

The search for dark matter is perhaps the highest priority of the "new physics" and could be the first to yield results if physicists get lucky. "We know that our theory of the universe has a gigantic hole in it," said Ye. "We do not understand dark matter or dark energy. There are theories of dark matter that say that if it does interact with matter, it will change the fundamental constants. If there is anything observable, it will come out of nuclear physics first. From that point of view, I think the connection is there, and it would be unwise not to take advantage of nuclear clocks to probe dark matter."

For the last half century, atomic clocks have been the standard to which all other clocks are calibrated. In these clocks, an electron in the outer shell of the atom is excited by electromagnetic radiation (such as light waves) and then re-emits radiation—as fluorescence—at a specific frequency. The high precision and reproducibility of this measurement led the physics community to adopt, in 1967, a new standard for the measurement of time [6]. They defined a second as the length of time it takes for a particular microwave emitted by cesium atoms to oscillate 9 192 631 770 times.

But this definition is starting to show its age. Cesium clocks using microwaves are no longer the most stable ones; atomic clocks based on strontium or ytterbium atoms have surpassed them. Cesium clocks are accurate to about 16 decimal places, while strontium clocks have already surpassed 18 decimal places [7].

"The definition is going to change within the next six to ten years," said Peik. However, he added, "Realistically, the thorium clock will not be one of the prime candidates," because the technology is not mature enough yet for round-the-clock operation. "But people say that maybe in the next generation we will use nuclear clocks." Indeed, Ye's team has already prepared for the intermediate phase, by synchronizing their nuclear clock measurements to a strontium clock. If the second is redefined to a strontium standard, they will be able to take full advantage of its increased precision.

In a nuclear clock, the absorption and emission of the laser photon occurs in the nucleus of the atom, which is much more sheltered from the atom's environment than the outer electrons are. In principle, this should make nuclear clocks more accurate. However, there is a problem. It takes a pretty big jolt to rouse the protons and neutrons in the nucleus to an excited state. Trying to do this with a beam of light is like firing a table-tennis ball at a bowling ball: The much heavier bowling ball will not even notice it has been hit.

But among the menagerie of high-mass atoms and their various isotopes, there is one unusual case: the Th-229 atom, which has 90 protons and 139 neutrons. In heavy nuclei, protons like to pair off with protons and neutrons with neutrons, and that leaves one

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neutron in Th-229 without a partner. There are lots of heavy atoms with an odd number of neutrons, but this neutron is special because it requires just a slight nudge to flip its spin, a so-called "spin transition." Only thorium has a spin transition that is so easy to activate. (The reason has to do with near cancellation of the "strong force" that holds the nucleus together and the electromagnetic force that tries to blow it apart.) Following the bowling ball analogy, one might say that the thorium "bowling ball" has a little switch on it. Hit that switch with the right size of table-tennis ball, and you get a light show.

Peik and co-author Christian Tamm proposed a clock based on this spin transition back in 2003 [8]. Early calculations indicated that the energy needed to "flip the switch" was much smaller (3.5 electron volts) than it turned out to be (8.4 electron volts). Because energy is proportional to frequency, physicists spent time looking for emissions in the wrong part of the electromagnetic spectrum. Another problem is that Th-229 is an unbelievably scarce commodity. Natural thorium exists almost solely as the Th-232 isotope, with 3 more neutrons that make it much more stable than Th-229. Th-229 is produced primarily as a byproduct of nuclear reactions. As a result, only 40 g of Th-229 exist in the world, most of it produced by the US nuclear weapons program. Anyone wanting to experiment with a thorium clock must make do with milligrams or micrograms of the stuff. And do not forget—it is highly radioactive. The portability of a nuclear clock is seen as one of its potential advantages, but that advantage would be lost if the clock required special handling due to radiation hazards.

The next 20 years saw gradual progress on the technological front, each laboratory contributing its own expertise. Peik's group developed widely tunable UV lasers covering the right frequency [9]. Thorsten Schumm, professor of quantum metrology at the Vienna University of Technology in Austria, developed tiny calcium fluoride crystals that are doped with a high density of Th-229 [10]. In late 2023, Peik measured the frequency of the nuclear transition to be about 2 020 409 billion hertz (i.e., oscillations per second) using crystals provided by Schumm [1]. These are impressive first steps, yet far from building a device competitive with atomic clocks. The uncertainty in Peik's measurement is billions of hertz. Ideally, for a nuclear clock, you would like to know the frequency down to a fraction of 1 hertz, or 16 digits of accuracy.

At this point Ye's lab stepped in with its special technology: a "frequency comb," which allowed their team to sample frequencies in much finer steps (and to sample many frequencies at a time, rather than one at a time). The Ye lab had been working on the development of such a UV frequency comb since 2002 [11]. In May 2024, just a few days after they received a Th-229-doped calcium fluoride crystal from Schumm, Ye and colleagues found what they were looking for: a set of 5 peaks emitting photons, with an average frequency at 2 020 407 384 335 thousand hertz. That is a million times more precise than Peik's measurement.

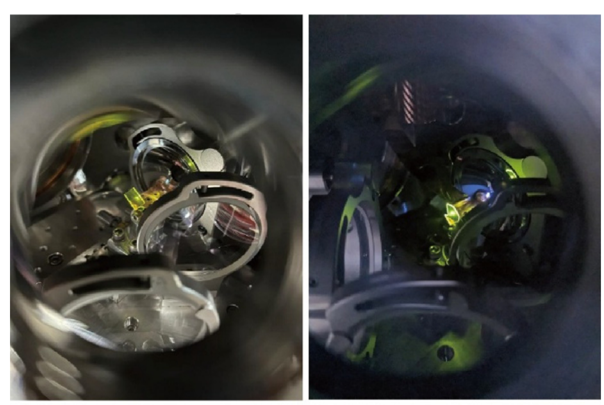
The five split peaks, rather than one, arise from interaction between the nucleus and the ambient electric field from the calcium fluoride crystal. This phenomenon is both an opportunity and a challenge, Ye said. On one hand, it shows that there are limits to the extent that the nucleus is sheltered from the external environment. On the other hand, it shows that the shift in frequency due to quantum interactions can be measured and perhaps compensated for.

Ye does not seem fazed by this difficulty, in part because he has another solution already in development: a thorium-doped thin film [12]. This would mitigate the scarcity issue of Th-229 because it would have about 1000 times fewer thorium atoms (and it would be 1000 times less radioactive than the crystals, too). "This can democratize its use," Ye said, eventually paving the way for the thorium clock to become a worldwide standard. Ye said he foresees a day when "If you can coat a mirror, you can have a nuclear clock."

While a lot of attention has been paid to possible exotic applications like dark matter and other "new physics," Ye said that one should not overlook the most obvious applications, to nuclear physics itself. Unlike the physics of electron orbitals, which are very well understood through the theory of quantum electrodynamics (QED), the nucleus is governed mostly by the "strong nuclear force" or quantum chromodynamics (QCD). "We do not understand the structure of the nucleus very well," Ye said. For instance, the five very closely spaced peaks in Th-229 reveal information about the size of the nucleus and its "quadrupole moment," which describes it (roughly speaking) as having an elongated shape, like an American football. For the first time, Ye's team could see the shape and measure the size of an atomic nucleus by using a laser to manipulate the nuclear state (Fig. 1).

It is this possibility of using spectroscopy to study the nucleus that excites Ye the most. "When lasers were introduced in the 1960s, atomic physics went through a revolution," he said. "With laser light, we were able to access the electron orbitals in such a controlled manner. Now that we can control the nuclear-clock transition, we can look into nuclear physics the same way."

Many questions must still be answered before nuclear clocks become a reality. What is the quietest environment for the thorium: a crystal, a thin film, or an ion trap? Can the effects of the environment be controlled or corrected for? How can the clock be made cheap? How can the radioactivity be reduced? But all of these seem like problems that can be managed, compared to the situation for the last two decades when the obstacles to a nuclear clock seemed insuperable. "I just want to develop the most unknown things to bring knowledge to humans," Ye said.



(a) (b)

Fig. 1. Photographs of the Ye team's experimental setup. In (a), a thorium-doped calcium fluoride crystal (center, light blue dot) has been prepared for a laser experiment. In (b), exposure to a UV laser, causes the thorium atoms in the crystal to give off their own radiation, whose frequency has been measured to 13 decimal places. The blue glow is ordinary fluorescence, resulting from excitation of the electrons in the Th-229-doped carrier crystal's fluorine atoms. At the same time, fluorescence of the thorium nuclei, or "thorescence," produces UV light, which is invisible to the human eye. Credit: Ye Labs, JILA, NIST, and University of Colorado, with permission.

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