

Developing a nuclear clock so precise it could redefine time

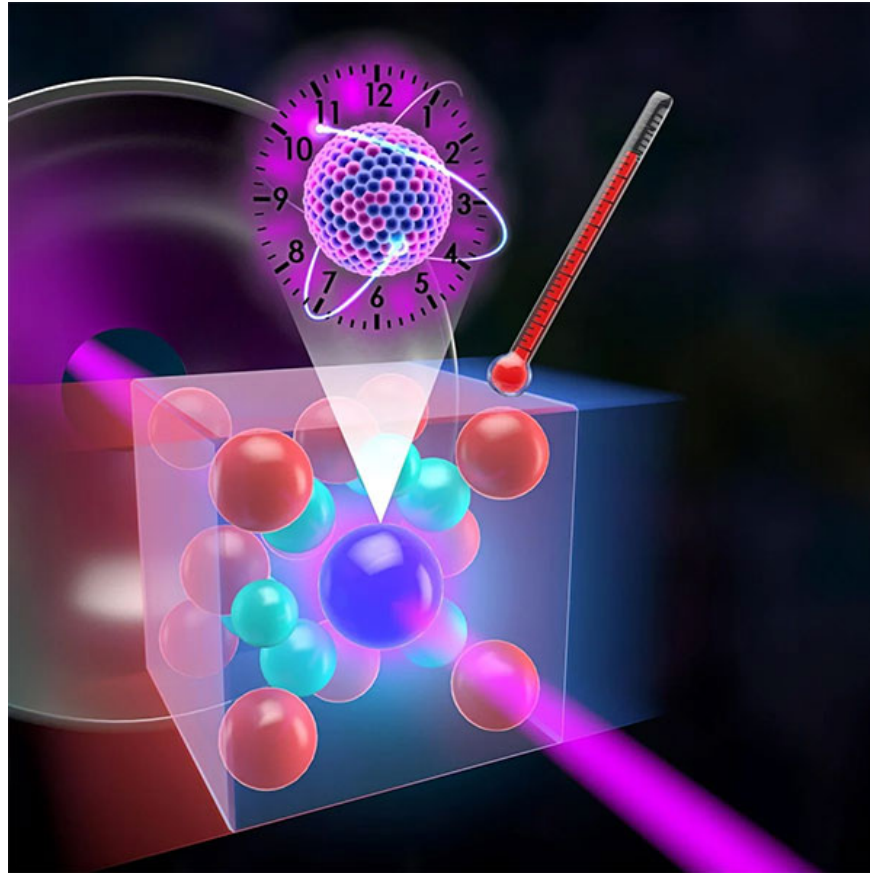
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Accuracy far surpasses atomic clocks

For decades, atomic clocks have set the standard for precise timekeeping, playing a vital role in GPS navigation, physics research, and fundamental science experiments. Now, researchers at JILA, led by physics professor Jun Ye and in collaboration with the Technical University of Vienna, are exploring a more stable alternative: nuclear clocks. Unlike atomic clocks that rely on electron transitions, this new type of clock relies on a low-energy transition inside the nucleus of the thorium-229 atom. Because nuclear transitions are less affected by environmental disturbances, thorium-based clocks could offer unprecedented stability and be used to test physical phenomena beyond the Standard Model.

Professor Ye and his colleagues have been researching nuclear clocks for years. Their groundbreaking experiment provided the first frequency-based measurement of thorium-229 nuclear transitions in a specially designed crystal. This confirmed that such transitions can be measured with sufficient precision to serve as a reliable timekeeping reference.



Effect of temperature on nuclear transformation

To develop a practical nuclear clock, scientists need to understand how external factors—particularly temperature—affect nuclear transitions. In a new experiment published in the journal *Physical Review Letters*, the team analyzed how the energy levels of thorium nuclei change as the crystal is heated to different temperatures. The research is an important step toward building an ultrastable nuclear timer.

'This is the first step in characterizing the nuclear clock system,' said Dr Jacob Higgins, a researcher at JILA and lead author of the experiment. 'We found a transition that is relatively insensitive to temperature, which is what we want for a precision timekeeping device.'

" Solid-state nuclear clocks have great potential to become a durable and portable timekeeping device with high precision ," Jun Ye emphasized. " We are looking for the parameter space where a compact nuclear clock can maintain 10^{-18} fractional frequency stability in continuous operation ."

Accuracy of nuclear clocks

Because the nucleus of an atom is less affected by environmental disturbances than its electrons, nuclear clocks can maintain accuracy under conditions where atomic clocks would struggle, due to their low sensitivity to noise. Of all the other nuclei, thorium-229 is particularly well suited for this purpose because it has an unusually low-energy nuclear transition, which makes it possible to probe with ultraviolet laser light rather than high-energy gamma rays.

Rather than measuring thorium in a trap-ion system, Ye's lab took a different approach: embedding thorium-229 in a solid material—a crystal of calcium fluoride (CaF₂). This method, developed by collaborators at the Technical University of Vienna, allows for a much higher density of thorium nuclei than traditional trap-ion techniques. More nuclei means a stronger signal and better stability for measuring nuclear transitions.

Warming up the nuclear clock

To see how temperature affects this nuclear transition, the researchers cooled and heated a thorium-containing crystal to three different temperatures: 150K (-123°C) with liquid nitrogen, 229K (-44°C) with a dry-methanol-refrigerant mixture, and 293K (about room temperature). Using a frequency comb laser, they measured the change in the nuclear transition frequency at each temperature, revealing two competing physical effects in the crystal.

One effect is that as the crystal is heated, it expands, slightly changing the crystal lattice and shifting the electric field gradient experienced by the thorium nuclei. This electric field gradient causes the thorium transition to split into multiple spectral lines, which shift in different directions as the temperature changes. The second effect is that the expansion of the crystal lattice also changes the charge density of the electrons in the crystal, changing the strength of the interaction of the electrons with the nuclei and causing the spectral lines to shift in the same direction.

When these two effects compete for control over thorium atoms, one particular transition is observed to be much less sensitive to temperature than the others, as the two effects nearly cancel each other out. Over the entire temperature range examined, this transition shifts by only 62 kilohertz, a shift that is at least 30 times smaller than the other transitions.

Next, the team plans to look for a temperature 'sweet spot' where the nuclear transitions are almost completely independent of temperature. Their initial data suggests that somewhere between 150K and 229K, the transition frequency becomes more easily temperature-stable, providing ideal operating conditions for a future nuclear clock.

Customizing the Nuclear Clock System

Building an entirely new type of clock required specially designed equipment, much of which did not yet exist at the required level of customization. Thanks to JILA's toolmaking workshop—with the help of machinists and engineers—the team was able to create the key components for the experiment.

Having in-house manufacturing expertise helped the researchers iterate on designs quickly and ensured that even small changes—like replacing crystals—could be made easily. They machined the crystal supports that hold the thorium-containing crystals, and fabricated parts of the cold-trap system that allow for precise temperature control.

Sensors beyond time

While the primary goal of this research is to develop a more stable nuclear clock, its implications extend far beyond measuring time. Thorium's nuclear transition is very insensitive to disturbances in its environment, but it is highly sensitive to changes in fundamental forces—any unexpected shift in its frequency could indicate new physical phenomena, such as the presence of dark matter.

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