How to make a nuclear clock tick

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Physicists are developing a device to monitor the invisible forces of the universe. Credit: CC0 via Unsplash

While not primarily useful for telling the time, nuclear clocks could allow scientists to test humankind's fundamental understanding of how reality works.

Thorsten Schumm is a clockmaker, but not the kind who sits at a workbench covered with springs and cogs, a magnifying loupe jammed into one eye. No, he is making a timepiece that is in an entirely different league.

Atomic clocks may sound familiar enough—but if Schumm's research goes to plan, it could result in a nuclear clock. And far from just telling the time, it could help crack some of the universe's most closely guarded secrets.

'This is still a dream,' said Schumm, a professor at the Vienna University of Technology in Austria. 'No one knows how to do it.'

He intends to change that and, in the process, to shed light on some of the fundamental forces of nature.

Split second

A clock can be based on anything that oscillates at regular intervals and can be read. The first clocks were mechanical. Many wristwatches today use the electromechanical oscillations of a quartz crystal.

But clock technology moved up a gear in the 1950s with the advent of atomic clocks.

Atoms are made up of a nucleus surrounded by an orbiting cloud of electrons. The tick of an atomic clock depends on the "quantum transitions" these electrons make.

It works like this. Electrons can absorb a packet of energy, which moves them from a "ground state" to an "excited state" of higher energy. Then they can fall back to the ground state, releasing that packet of energy on their way down.

These energy transitions occur with a particular frequency that can be used for timekeeping. This all happens astonishingly fast.

For instance, one second is officially defined as 9 192 631 770 oscillations of an energy packet that excites a caesium-133 atom.

Atomic clocks are so precise because they produce an awful lot of oscillations, or ticks. So, if the readout mechanism misses one or two of them, it generally isn't much of a problem when there are more than 9 billion per second.

Nuclear clocks are different. The tick wouldn't depend on electrons but rather on the vibrations of the nucleus itself. These are many times faster than the ticks of the electron transitions.

But, as Schumm says, work continues on getting a nuclear clock up and running.

Happy coincidence

He got interested in solving this nuclear mystery partly out of serendipity.

It turns out that a rare isotope of the element thorium-229 is by far the easiest material from which a nuclear clock might be built. That's because it is thought to have the slowest ticks of any nucleus. Plus, the institute where Schumm works is one of the few places that can access this material.

Thorium-229 isn't naturally occurring. It is produced only through the nuclear decay of certain types of uranium.

The Vienna University of Technology has an agreement with Oakridge

National Laboratory in the US that allows it to obtain some thorium-229 from leftover uranium used in nuclear tests decades ago.

It wasn't lost on Schumm that his first name and the name of the element are both derived from the mythical Norse god, Thor.

'That tickled me,' he said.

It's about time

Since 2020, Schumm has been conducting basic research on creating a nuclear clock under the EU-funded ThoriumNuclearClock project running until early 2026.

He and his colleague Professor Ekkehard Peik of Germany's National Metrology Institute in Braunschweig share the project's role of principal investigators, along with Marianna Safronova from the University of Delaware in the US and Peter Thirolf from LMU Munich in Germany.

To set a nuclear clock ticking, it needs a nudge with a laser set to exactly the right energy level. But for most nuclei, the energy frequency required is nowhere near accessible with current laser technology.

Thorium-229 is one of the largest stable nuclei that exist. It was thought it could adopt a state with a very low energy that current lasers could reach—though no one really understands how or why it does this.

'To begin with, it wasn't even really clear that this state of thorium-229 existed,' said Schumm.

Now it's known that it does exist. In 2020, Schumm and his colleagues published a measurement of the isotope's energy level. Since then, they have continued to build on that knowledge.

All of that opens the way to testing the clock for real. Schumm and his fellow researchers have been working on building a laser that is custom-designed to tickle the thorium at exactly the right frequency.

Soon they plan to direct this laser at some trapped thorium atoms for the first time in a bid to start them ticking.

'We are very excited about the outcome of this experiment because it is something that has never been done before,' said Peik. 'We and others have tried related experiments with thorium-229 in the past without success. This time we feel we are much better prepared.'

Crystal clear

For those experiments, the thorium atoms will be held in atomic traps—a very finicky business. So, while ThoriumNuclearClock was already under way, Schumm also lead a two-year EU-funded project called CRYSTALCLOCK, which aimed to develop a simpler design and readout mechanism for a nuclear clock.

The idea here was to grow a crystal consisting of calcium fluoride and have a scattering of thorium-229 atoms distributed through the material. This provides a solid material that is far easier to work with than the atomic traps.

Schumm and his colleagues, including Dr. Tomas Sikorsky, published a paper demonstrating that these thorium-doped crystals could be grown in 2022. The next step will be to start working out how the tick of these crystals can be read.

Schumm says that a technique called nuclear tomography could be adapted for this purpose and the whole process would be much easier than using thorium atoms in traps.

Forces of nature

This is worth all the bother not because more precise clocks are needed but rather because humankind's fundamental understanding of how reality works can be tested.

The best theories of physics explain that the universe has four fundamental forces: gravity, electromagnetism, the weak nuclear force and the strong nuclear force. The strength of these forces is known and those numbers are often referred to as fundamental "constants".

But it isn't know whether the strength of these forces has been, and will always be, the same. There are indications that the forces were much stronger in the distant past, close to the Big Bang, and they may even still be changing by the merest amount.

Atomic and nuclear clocks may make it possible to put that to the test. The tick of an atomic clock is predominantly affected by the strength of electromagnetism, so if the speed of the tick began to change that would suggest a drift in the underlying force.

However, electromagnetism is very weak, so atomic clocks, despite their breathtaking precision, may never be able to pick up any change to it.

Nuclear clock ticks are, by contrast, influenced by the strong force. So, if and when a working nuclear clock were to be created, it could be used to monitor whether there are any changes to the strong force over periods of time.

'Going from atoms to nuclei isn't about getting a better clock,' said Schumm. 'In fact, it's likely that the first nuclear clock won't be as good as the best atomic clocks. The point is more about having a completely new kind of technology that could basically test the strong force.'

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