# A rock is a clock: Physicists use matter to measure time

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Quantum mechanically, mass can be used to measure time and vice versa. Credit: Holger Müller lab

What is the simplest, most fundamental clock? Physicist Holger Müller and his UC Berkeley colleagues have shown that a single atom is sufficient to measure time using its high-frequency matter wave. Conversely, the frequency of matter can be used to define its mass. The feat is a fundamental demonstration of wave-particle duality central to quantum mechanics.

Ever since he was a kid growing up in Germany, Holger Müller has been asking himself a fundamental question: What is time?

That question has now led Müller, today an associate professor of physics at the University of California, Berkeley, to a fundamentally new way of measuring time.

Taking advantage of the fact that, in nature, matter can be both a particle and a wave, he has discovered a way to tell time by counting the oscillations of a matter wave. A matter wave's frequency is 10 billion times higher than that of visible light.

"A rock is a clock, so to speak," Müller said.

In a paper appearing in the Jan. 11 issue of *Science*, Müller and his UC Berkeley colleagues describe how to tell time using only the matter wave of a cesium atom. He refers to his method as a Compton clock because it is based on the so-called Compton frequency of a matter wave.

"When I was very young and reading science books, I always wondered why there was so little explanation of what time is," said Müller, who is also a guest scientist at Lawrence Berkeley National Laboratory. "Since then, I've often asked myself, 'What is the simplest thing that can measure time, the simplest system that feels the passage of time?' Now we have an upper limit: one single massive particle is enough."

While Müller's Compton clock is still 100 million times less precise than today's best atomic clocks, which employ aluminum ions, improvements in the technique could boost its precision to that of atomic clocks, including the cesium clocks now used to define the second, he said.

"This is a beautiful experiment and cleverly designed, but it is going to be controversial and hotly debated," said John Close, a quantum physicist at The Australian National University in Canberra. "The question is, 'Is the Compton frequency of atoms a clock or not a clock?' Holger's point is now made. It is a clock. I've made one, it works."

Müller welcomes debate, since his experiment deals with a basic concept of quantum mechanics – the wave-particle duality of matter – that has befuddled students for nearly 90 years.

"We are talking about some really fundamental ideas," Close said. "The discussion will create a deeper understanding of quantum physics."

Müller can also turn the technique around to use time to measure mass. The reference mass today is a platinum-iridium cylinder defined as weighing one kilogram and kept under lock and key in a vault in France, with precise copies sparingly dispersed around the world. Using Müller's matter wave technique provides a new way for researchers to build their own kilogram reference.

De Broglie's "crazy" idea

The idea that matter can be viewed as a wave was the subject of the 1924 Ph.D. thesis by Louis de Broglie, who took Albert Einstein's idea that mass and energy are equivalent ($E=mc^2$) and combined it with Ernst Planck's idea that every energy is associated with a frequency. De Broglie's idea that matter can act as a wave was honored with the Nobel Prize in Physics in 1929.

Using matter as a clock, however, seemed far-fetched because the frequency of the wave, called the Compton, or de Broglie, frequency, might be unobservable. And even if it could be seen, the oscillations would be too fast to measure.

Müller, however, found a way two years ago to use matter waves to confirm Einstein's gravitational redshift – that is, that time slows down in a gravitational field. To do this, he built an atom interferometer that treats atoms as waves and measures their interference.

"At that time, I thought that this very, very specialized application of matter waves as clocks was it," Müller said. "When you make a grandfather clock, there is a pendulum and a clockwork that counts the pendulum oscillations. So you need something that swings and a clockwork to make a clock. There was no way to make a clockwork for matter waves, because their oscillation frequency is 10 billion times higher than even the oscillations of visible light."

One morning last year, however, he realized that he might be able to combine two well-known techniques to create such a clockwork and explicitly demonstrate that the Compton frequency of a single particle is, in fact, useful as a reference for a clock. In relativity, time slows down for moving objects, so that a twin who flies off to a distant star and returns will be younger than the twin who stayed behind. This is the so-called twin paradox.

Similarly, a cesium atom that moves away and then returns is younger than one that stands still. As a result, the moving cesium matter wave will have oscillated fewer times. The difference frequency, which would be around 100,000 fewer oscillations per second out of 10 million billion billion oscillations ($3 \times 10^{25}$ for a cesium atom), might be measurable.

In the lab, Müller showed that he could measure this difference by allowing the matter waves of the fixed and moving cesium atoms to interfere in an atom interferometer. The motion was caused by bouncing photons from a laser off the cesium atoms. Using an optical frequency comb, he synchronized the laser beam in the interferometer with the difference frequency between the matter waves so that all frequencies were referenced solely to the matter wave itself.

"Our clock is accurate to within 7 parts per billion," he said. "That's like measuring one second out of eight years, about as good as the very first cesium atomic clock about 60 years ago. Maybe we can develop it further and one day define the second as so many oscillations of the Compton frequency for a certain particle."

Müller's proposal to make a mass standard based on time provides a new way to realize plans by the international General Conference on Weights and Measures to replace the standard kilogram with a more fundamental measure. It will involve an incredibly pure crystal of silicon, dubbed an Avogadro sphere, which is manufactured so precisely that the number of atoms inside is known to high accuracy.

"Our clock and the current best Avogadro spheres would make one of the best realizations of the newly defined kilogram," he said. "Knowing the ticking rate of our clock is equivalent to knowing the mass of the particle, and once the mass of one atom is known, the masses of others can be related to it."

And what about the question, What is time? Müller says that "I don't think that anyone will ever have a final answer, but we know a bit more about its properties. Time is physical as soon as there is one massive particle, but it definitely is something that doesn't require more than one massive particle for its existence. We know that a massless particle, like a photon, is not sufficient."

Müller hopes to push his technique to even smaller particles, such as electrons or even positrons, in the latter case creating an antimatter clock . He is hopeful that someday he'll be able to tell time using quantum fluctuations in a vacuum.

Müller's coauthors are post-doctoral fellows Shau-Yu Lan, Michael A. Hohensee and Damon English; graduate students Pei-Chen Kuan and

Brian Estey; and Miller Postdoctoral fellow Justin M. Brown. All are in UC Berkeley's Department of Physics. The work was supported by the Alfred P. Sloan Foundation, the David and Lucile Packard Foundation, the National Institute of Standards and Technology, the National Science Foundation and the National Aeronautics and Space Administration.

**More information:** "A Clock Directly Linking Time to a Particle's Mass," by S.-Y. Lan et al., *Science*, 2013.

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