Pair of aluminum atomic clocks reveal Einstein's relativity at a personal scale

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NIST physicists compared a pair of the world's best atomic clocks to demonstrate that you age faster when you stand just a couple of steps higher on a staircase. Credit: Loel Barr for NIST

Scientists have known for decades that time passes faster at higher elevations—a curious aspect of Einstein's theories of relativity that previously has been measured by comparing clocks on the earth's surface and a high-flying rocket.

Now, physicists at the National Institute of Standards and Technology (NIST) have measured this effect at a more down-to-earth scale of 33 centimeters, or about 1 foot, demonstrating, for instance, that you age faster when you stand a couple of steps higher on a staircase.

Described in the Sept. 24 issue of *Science*,* the difference is much too small for humans to perceive directly—adding up to approximately 90 billionths of a second over a 79-year lifetime—but may provide practical applications in geophysics and other fields.

Similarly, the NIST researchers observed another aspect of relativity—that time passes more slowly when you move faster—at speeds comparable to a car travelling about 20 miles per hour, a more comprehensible scale than previous measurements made using jet aircraft.

NIST scientists performed the new "time dilation" experiments by comparing operations of a pair of the world's best experimental atomic clocks. The nearly identical clocks are each based on the "ticking" of a single aluminum ion (electrically charged atom) as it vibrates between two energy levels over a million billion times per second. One clock keeps time to within 1 second in about 3.7 billion years (see www.physorg.com/news184517462.html) and the other is close behind in performance. The two clocks are located in different laboratories at NIST and connected by a 75-meter-long optical fiber.

NIST's aluminum clocks—also called "quantum logic clocks" because they borrow logical decision-making techniques from experimental quantum computing—are precise and stable enough to reveal slight differences that could not be seen until now. The clocks operate by shining laser light on the ions at optical frequencies, which are higher than the microwave frequencies used in today's standard atomic clocks based on the cesium atom.

Optical clocks could someday lead to time standards 100 times more accurate than today's standard clocks.

The aluminum clocks can detect small relativity-based effects because of their extreme precision and high "Q factor"—a quantity that reflects how reliably the ion absorbs and retains optical energy in changing from one energy level to another—says NIST postdoctoral researcher James Chin-Wen Chou, first author of the paper.

"We have observed the highest Q factor in atomic physics," Chou says. "You can think about it as how long a tuning fork would vibrate before it loses the energy stored in the resonating structure. We have the ion oscillating in sync with the laser frequency for about 400 thousand billion cycles."

The NIST experiments focused on two scenarios predicted by Einstein's theories of relativity. First, when two clocks are subjected to unequal gravitational forces due to their different elevations above the surface of the Earth, the higher clock—experiencing a smaller gravitational force—runs faster. Second, when an observer is moving, a stationary clock's tick appears to last longer, so the clock appears to run slow. Scientists refer to this as the "twin paradox," in which a twin sibling who travels on a fast-moving rocket ship would return home younger than the other twin. The crucial factor is the acceleration (speeding up and slowing down) of the travelling twin in making the round-trip journey.

NIST scientists observed these effects by making specific changes in one of the two aluminum clocks and measuring the resulting differences in the two ions' relative ticking rates, or frequencies.

In one set of experiments, scientists raised one of the clocks by jacking up the laser table to a height one-third of a meter (about a foot) above the second clock. Sure enough, the higher clock ran at a slightly faster rate than the lower clock, exactly as predicted.

The second set of experiments examined the effects of altering the physical motion of the ion in one clock. (The ions are almost completely motionless during normal clock operations.) NIST scientists tweaked the one ion so that it gyrated back and forth at speeds equivalent to several meters per second. That clock ticked at a slightly slower rate than the second clock, as predicted by relativity. The moving ion acts like the traveling twin in the twin paradox.

Such comparisons of super-precise clocks eventually may be useful in geodesy, the science of measuring the Earth and its gravitational field, with applications in geophysics and hydrology, and possibly in space-based tests of fundamental physics theories, suggests physicist Till Rosenband, leader of NIST's aluminum ion clock team.

NIST scientists hope to improve the precision of the aluminum clocks even further, as much as 10-fold, through changes in ion trap geometry and better control of ion motion and environmental interference. The aim is to measure differences in timekeeping well enough to measure heights to an accuracy of 1 centimeter, a performance level suitable for making geodetic measurements. The paper suggests that optical clocks could be linked to form a network of "inland tidal gauges" to measure the distance from the earth's surface to the geoid (the surface of the earth's gravity field that matches the global mean sea level). Such a network could be updated far more frequently than current techniques.

More information: *C.W. Chou, D.B. Hume, T. Rosenband and D.J. Wineland. Optical Clocks and Relativity. *Science*. Sept. 24, 2010.

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