General relativity tested on a tabletop

Atomic-clock experiment pins down accuracy of fundamental gravity measurement.

By measuring a spectacularly small difference in the ticks of two quantum clocks, physicists have proven a pillar of Albert Einstein's theory of gravity to be on firmer footing than ever before.

The experiment is the latest in a series of tests in which scientists have scrutinized one of Einstein's more profound predictions: that clocks in stronger gravitational fields run more slowly. For decades they have put clocks at higher elevations, where Earth's gravity is slightly weaker, and measured the ensuing changes. From a clock in a tower at Harvard University in Cambridge, Massachusetts, in the 1960s, to others flown on planes in the 1970s, to a clock that flew thousands of kilometres into space on a rocket in 1980, physicists have not been able to show that Einstein was wrong.

Now, a team led by Holger Müller of the University of California, Berkeley, has measured the time-shifting effects of gravity 10,000 times more accurately than ever before. They show that gravity's effect on time is predictable to 7 parts per billion (H. Müller, A. Peters and S. Chu *Nature* **463,** 926–929; 2010). And they did it using two laboratory clocks with a height difference of just 0.1 millimetres — a set-up that seems quaintly small in this day of big physics. "Precision experiments on a tabletop are not something of the past," says Müller, whose research team consisted of Achim Peters of the Humboldt University of Berlin and Steven Chu, the US Secretary of Energy.

Many atomic clocks use the extremely regular pulsations of atoms shifting between excited energy states. But Müller's apparatus relied on the fundamental quantum frequency of a caesium atom associated with the atom's rest energy. This frequency was so high that physicists never thought to use it as a clock. But a special interferometer could measure the difference between two such clocks experiencing gravity's effect.

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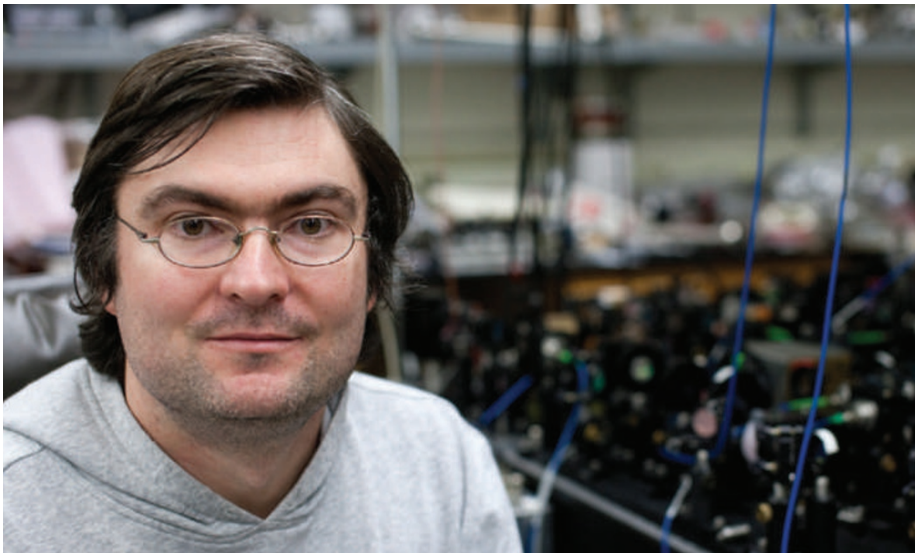
"What's fascinating about their work is that they were using the entire atom as a clock," says atomic-clock expert Jun Ye of the Joint Institute for Laboratory Astrophysics in Boulder, Colorado.

Müller and his team shot caesium atoms, cooled nearly to absolute zero, in an arc across a gap. Mid-stream, photons from a laser bumped the atoms into two, quantum-mechanical alternate realities. In one, an atom absorbed a photon and arced on a slightly higher path, experiencing a tiny weakening of gravity and speed-up of time. In the other, the atom stuck to the lower path, where gravity was stronger and time moved slightly more slowly. A difference in phase in the atom's fundamental frequency, measured by the interferometer, indicated a tiny difference in time.



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Holger Müller used laser-trap technology to test one of Einstein's predictions from general relativity.

Laser traps

The experiment takes advantage of the laser atom trap, for which Chu won a Nobel prize in 1997. The data for the current study were obtained shortly after that, when Chu was using the set-up to measure a different constant, the acceleration of gravity (A. Peters, K. Y. Chung and S. Chu *Nature* **400,** 849–852; 1999).

But Müller says that in October 2008, he had an epiphany that the same data could be used to show the constancy of gravity's effect on time. He e-mailed Chu, then the director of the Lawrence Berkeley National Laboratory in Berkeley, California, who responded three days later saying it was a good idea.

Chu says in an e-mail that he found time to work on the current study during nights, weekends and on planes — after putting in 70–80-hour weeks as energy secretary. "I like juggling a lot of balls," he says.

The result could one day have practical applications. If gravity's time-shifting effect were not constant, then researchers might have had to worry about the accuracy of new atomic clocks as they are flown into orbit on Global Positioning System (GPS) satellites. But Müller has demonstrated the effect to be extraordinarily consistent. "Now we know that the physics is fine," he says.

The test also puts pressure on the Atomic Clock Ensemble in Space (ACES), an experiment being run by the European Space Agency that is due to be attached to the International Space Station in 2013. The current study already betters ACES's planned measurement of gravity's time-shifting effect by almost three orders of magnitude. ACES's principal investigator Christophe Salomon says that the mission will cost about €100 million (US$136 million), plus the cost of a launch rocket. By comparison, Müller says that his tabletop apparatus cost much less than $1 million. Salomon says that ACES is still justified because it will perform two other fundamental physics tests, as well as help researchers to improve the coordination of ground-based atomic clocks.

Physicist Clifford Will of Washington University in St Louis, Missouri, says that Müller's result narrows the window for the alternative theories of gravity that some theorists are exploring. Will was also impressed that Chu found time to contribute to the study. "When was the last time that a sitting member of the president's cabinet had a paper in *Nature* on fundamental physics?" he asks. ■

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