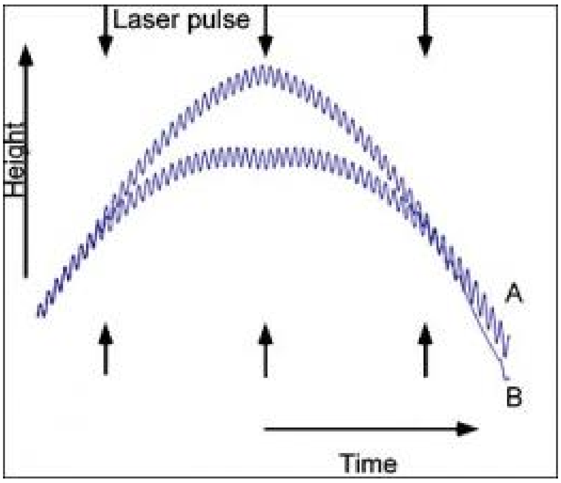
Most precise test yet of Einstein's gravitational redshift

17 February 2010, By Robert Sanders



Cesium atom matter waves oscillate more slowly along the lower path because the gravitational field is stronger, which means time passes more slowly. In the experiment, laser pulses kicked half the atoms 0.1 mm higher than the others; a second laser sent them on a course to merge; and a third laser measured the phase difference between the interfering matter waves. (Courtesy of Nature magazine)

(PhysOrg.com) -- While airplane and rocket experiments have proved that gravity makes clocks tick more slowly - a central prediction of Albert Einstein's general theory of relativity - a new experiment in an atom interferometer measures this slowdown 10,000 times more accurately than before, and finds it to be exactly what Einstein predicted.

The result shows once again how well Einstein's theory describes the real world, said Holger Müller, an assistant professor of physics at the University of California, Berkeley.

"This experiment demonstrates that gravity changes the flow of time, a concept fundamental to the theory of general relativity," Müller said. The phenomenon is often called the gravitational redshift because the oscillations of light waves slow down or become redder when tugged by gravity.

A report describing the experiment appears in the Feb. 18 issue of the journal *Nature*.

Treating particles as waves

Müller tested Einstein's theory by taking advantage of a tenet of quantum mechanics: that matter is both a particle and a wave. The cesium atoms used in the experiment can be represented by matter waves that oscillate 3x1025 times per second, that is, 30 million billion billion times per second.

When the cesium atom matter wave enters the experiment, it encounters a carefully tuned flash of laser light. The laws of quantum mechanics step in, and each cesium atom enters two alternate realities, Müller said. In one, the laser has pushed the atom up one-tenth of a millimeter - 4/1000 of an inch - giving it a tiny boost out of Earth's gravitational field. In the other, the atom remains unmoved inside Earth's gravitational well, where time flies by less quickly.

While the frequency of cesium matter waves is too high to measure, Müller and his colleagues used the interference between the cesium matter waves in the alternate realities to measure the resulting difference between their oscillations, and thus the redshift.

The equations of general relativity predicted precisely the measured slowing of time, to an accuracy of about one part in 100 million (7x10-9) - 10,000 times more accurate than the measurements made 30 years ago using two hydrogen maser clocks, one on Earth and the other launched via rocket to a height of 10,000 kilometers.

"Two of the most important theories in all of physics are Quantum Mechanics and the General Theory of

Relativity," noted Müller's collaborator, Steven Chu, a former UC Berkeley professor of physics and former director of Lawrence Berkeley National Laboratory (LBNL). Chu was one of the originators of the atom interferometer, which is based on his Nobel Prize-winning development of cold laser traps. "The paper that we are publishing in Nature uses two fundamental aspects of the quantum description of matter to perform one of the most precise tests of The General Theory of Relativity."

Precision timekeeping

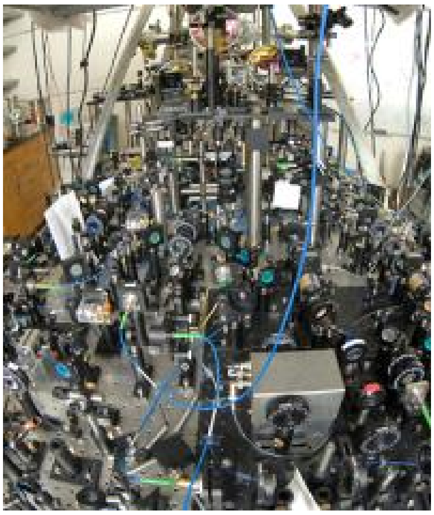
Far from merely theoretical, the results have implications for Earth's global positioning satellite system, for precision timekeeping and for gravitational wave detectors, Müller said.

"If we used our best clocks, with 17-digit precision, in global positioning satellites, we could determine position to the millimeter," he said. "But lifting a clock by 1 meter creates a change in the 16th digit. So, as we use better and better clocks, we need to know the influence of gravity better."

Müller also noted that the experiment demonstrates very clearly "Einstein's profound insight, that gravity is a manifestation of curved space and time, which is among the greatest discoveries of humankind."

This insight means that what we think of as the influence of gravity - planets orbiting stars, for example, or an apple falling to Earth - is really matter following the quickest path through spacetime. In a flat geometry, the quickest route is a straight line. But in Einstein's theory, the flow of time becomes a function of location, so the quickest path could now be an elliptical orbit or a plumb line to the ground.

Experiments have tested the theory to higher and higher precision, but direct measurements of the gravitational redshift have had to struggle with the minimal size of the effect in Earth's gravitational field. These measurements culminated in the 1976 experiment by NASA and the Harvard Smithsonian Astrophysical Observatory using hydrogen maser clocks. That precision was 7x10-5.



The mirrors and lenses on this optical bench prepare six lasers to capture cold atoms in the atom interferometer (at rear). (Damon English/UC Berkeley)

Atom interferometers

Just as an optical interferometer uses interfering light waves to measure time or distance to within to a fraction of a wavelength, an atom interferometer uses interfering matter waves. Because matter waves oscillate at a much higher frequency than light waves, they can be used to measure correspondingly smaller times and distances.

Since 1991, when Chu was at Stanford University, he and former members of his lab have used Chu's technique of cooling and trapping atoms with lasers to build the most precise atom interferometers. In 1999, one of those students, Achim Peters, now at Humboldt University in Berlin, performed such an experiment on cesium atoms in free fall to precisely measure the acceleration of gravity.

Müller, who was Peters' graduate student at Humboldt University, subsequently worked in Steve Chu's group at Stanford as a postdoctoral fellow, although Chu left Stanford during that time to become the director of LBNL and later U.S. Secretary of Energy. After joining the UC Berkeley faculty in July 2008, Müller attended a conference on frequency and time measurement where he realized that Peters' experimental data could also yield the most precise measure yet of the gravitational redshift. Müller approached Chu about the experiment and received an enthusiastic response.

Peters' experiment involved capturing a million cesium atoms in a cold laser trap chilled to a few millionths of a degree above absolute zero and zapping them with a vertical laser beam tuned to give them a kick upwards, with 50 percent probability. A split second later, a second laser pulse sends the high-flying matter waves downward and the stationary ones upward to merge. A third laser pulse recombines the two. Measuring the amplitude of the recombined matter waves reveals the phase difference between the two.

Müller and Chu noted that the contribution of the rest mass to the frequency of matter wave oscillations is normally ignored in quantum mechanical calculations, because the resulting frequencies are too fast to measure. But in this experiment, that high "Compton" frequency allowed an extremely precise measurement of the different clock rates.

"In conceiving of this research, we realized that relativity theory demands that the energy E also includes the energy due to the rest mass of the atom, given by Einstein's famous equation E = mc2," Chu wrote in an e-mail. "The energy due to the rest mass of the atoms is enormous, resulting in an atomic clock that ticks at 3x1025 Hertz."

Freefall

During the approximately 0.3 seconds of freefall, the matter waves on the higher route feel that a little more time elapsed: just 2x10-20 seconds compared to the lower route. But because of the sheer magnitude of the Compton frequency, Müller said, they oscillated about a million times more often. Since the atom interferometer could measure the difference to within a thousandth of an oscillation, the experiment produced a 9-digit accuracy. This corresponds to measuring the time difference to 10-28 seconds.

To put these numbers in perspective, Müller said, "if the time of freefall was extended to the age of the universe, 14 billion years, the time difference between the upper and lower routes would be a mere 1/100th second, and the accuracy of the measurement would be 60 picoseconds, the time it takes for light to travel about 1/2 inch."

Müller is building ever more precise atom interferometers, and hopes this year to measure the gravitational redshift more precisely with a millimeter separation. One future milestone will be a separation of a meter or more.

"If we could separate the atoms by a meter, we could build an experiment to observe gravity waves," he said. Gravity waves are tiny fluctuations in gravity propagating through spacetime theoretically generated by interactions between massive stars or black holes.

To filter out noise from Earth's gravity and other perturbations, like a passing truck, such an experiment would have to involve at least two atom interferometers separated by a large distance. An ideal spot for the experiment, he said, would be the Deep Underground Science and Engineering Laboratory at the former Homestake mine in South Dakota.

Provided by University of California - Berkeley

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