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Steering atoms toward better navigation, physicists test Newton and Einstein along the way

February 18 2007

Stanford physicist Mark Kasevich has adapted the technology in today's airplane navigation systems to work with atoms so cold that they almost stand still. At temperatures scarcely above absolute zero, atoms no longer behave as particles but rather as de Broglie waves, named for the theorist who originally posited that all matter behaves as both a light wave and as a particle. These waves can be configured to add or subtract, or interfere, with one another in an interferometer-an instrument that is used on airplanes to measure very small changes in rotation.

Since global positioning system (GPS) location information is not available everywhere, airplanes still use inertial navigation systems founded on laser-based interferometers, even though their accuracy drifts over time. Kasevich's "atomic interferometer" may form the basis of a next-generation navigation system that gauges the airplane's location much more accurately.

"Navigation problems-how to get from point A to point B-tell us about space-time," says Kasevich, a professor in the departments of Physics and Applied Physics who spoke about atomic sensors Feb. 17 in San Francisco at the annual meeting of the American Association for the Advancement of Science (AAAS). "When we build these de Broglie wave navigation sensors, we're also building sensors that can test these fundamental laws about space-time."

Kasevich's atomic interferometer also is a sensitive detector of gravity-by far the weakest of the four fundamental forces of physics. Kasevich and his research group are using the interferometer to measure the gravitational constant, G, to greater precision than has ever been reached in the more than three centuries since Isaac Newton put forward his law of universal gravitation. Moreover, Kasevich is putting another physics legend to the test in ongoing research of Einstein's century-old principle of equivalence, which states it is impossible to tell the difference between the acceleration of an object due to gravity and the acceleration of its frame of reference.

The panel in which Kasevich is speaking is titled "What's Hot in Cold." Other participants include Tom Shachtman, author of the nonfiction book Absolute Zero and the Conquest of Cold, as well as physicists Heather Lewandowski of the University of Colorado-Boulder; Steven M. Girvin of Yale University; Richard Packard of the University of California-Berkeley; and Moses Chan of Pennsylvania State University-University Park. They will describe how matter cooled to low temperatures behaves according to the laws of quantum mechanics, which operate quite differently from the familiar world of classical physics. Whether gas, liquid or solid, each system in this ultracool regime proves to be a rich trove of new physics.

Interferometry-old and new

Navigation technology inspired Kasevich's atomic sensors. Airplanes monitor their attitude with ring-laser gyroscopes, which use interferometry to detect rotation. In conventional interferometers, a single-wavelength beam from a laser is split into two paths and later recombined so that the final wave exhibits a characteristic pattern. This interference pattern will differ depending upon the differences in paths traveled by the two split waves. If the paths are identical, they will recombine as the original wave. But as the airplane with its gyroscope turns, rotation of the interferometer inside changes one split wave's path relative to the other, and the difference causes the recombined wave to partially dim. With a large enough shift between the split paths, the recombined wave can vanish entirely in what is known as total destructive interference.

Kasevich's team applies this principle using not laser light but cesium atoms. As an atom is cooled to very low temperatures, below minus-459 F, its velocity slows to zero, and-due to the principles of quantum mechanics-the atom begins to behave like a wave, just as in Louis de Broglie's Nobel Prize-winning prediction of 1923. The colder and therefore slower the cesium atom becomes, the longer its wavelength. Ultimately these wave-like atoms can get so cold that they reach wavelengths comparable to visible light. And they can be split and made to recombine just as in a conventional laser interferometer, yielding the atomic interferometer.

The most bizarre property of the atomic interferometer, Kasevich says, is that total destructive interference makes atoms seem to disappear.

"Nature lets me take this atom, split it in half and bring it back together," he says. "The cesium atom is in two places at once, and nature lets it do that. You can't do that with marbles."

But matter is neither created nor destroyed. "We're manipulating the probability of where we find the matter in space," Kasevich clarifies.

Substituting an atomic interferometer for a conventional one inside an airplane's ring-laser gyroscope would yield an atomic gyroscope. The atomic gyroscope, if it could be produced at a portable size, would be a desirable replacement for ring-laser gyroscopes because the older technology loses accuracy in gauging the airplane's location to the tune of about 1 mile (1852 meters) per hour. By comparison, an atomic sensor could lead to drifts of around 16 feet (5 meters) per hour-three one-thousandths of the error.

G attracts Kasevich's interest

Besides their potential for improving navigation accuracy, Kasevich's atomic interferometers or sensors also are sensitive enough to detect changes in the split wave induced by gravity. The level of sensitivity is fine enough to be able to detect changes in gravity at levels below one part per billion. Gravity is the longest known of all fundamental physical forces. Kasevich's group continues to work to refine the atomic sensors in hopes of measuring Newton's gravitational constant G beyond the level of precision at which it has been measured-a figure that has not improved much since British natural philosopher Henry Cavendish published the first measurement more than two centuries ago.

"We want to add our voice to the chorus of 'What is G really?'" says Kasevich.

Another mystery that ultracold atoms may help solve is Einstein's equivalence principle, which to date hasn't been proved or refuted. In his equivalence principle, Einstein asserted the gravitation experienced while standing on a massive body, such as Earth, is the same as the pseudo-force experienced by an observer in an accelerated frame of reference. Just like a spinning dancer's body causes her skirt to twirl, the revolving Earth drags space and time around it, providing the frame of reference from which we determine positions and movements.

An ongoing experiment to test this principle is set up in a 10-meter-tall tube installed in the basement of the Varian Physics Building at Stanford. It employs isotopes-atoms of a chemical element with the same atomic number and nearly identical chemical behavior but with different atomic masses. Two different isotopes of rubidium are cooled to ultralow temperature and released into free fall. The wave-like atoms fall very slowly, "like releasing a fistful of sand," Kasevich says. If the two isotopes, which have slightly different masses, accelerate at differing rates as measured with atomic interferometry, this means the principle of equivalence fails.

The implications are profound, Kasevich says. "If Einstein's equivalence principle doesn't hold, that means that we would have to rethink the law of physics at a very basic level."

Source: Stanford University

Citation: Steering atoms toward better navigation, physicists test Newton and Einstein along the way (2007, February 18) retrieved 19 April 2024 from https://phys.org/news/2007-02-atoms-physicists-newton-einstein.html