either theoretical or observational, to expect any violation of the weak equivalence principle. But because the material compositions of the Earth and the Moon are so different, one could imagine that a violation of the weak equivalence principle between them just happens to be roughly equal and opposite to a gravitational-self-energy effect of the kind that the theorists *do* expect at some level. The Seattle group's laboratory experiment was intended to exclude (or confirm) just that sort of adventitious violation of the weak equivalence principle.

"You might object that a compositional effect that hides a gravitational-self-energy anomaly would be highly implausible," says Adelberger. "But physics is an empirical science. It's not philosophy. And the equivalence principle is so very important that you have to test it as well as you possibly can."

Testing the strong equivalence principle requires the monitoring of large astronomical bodies. But the weak equivalence principle was already being tested in the Budapest laboratory of Baron Roland von Eötvös early in the century. Like the baron, the Seattle group uses a sensitive torsion pendulum to look for differences in the gravitational interaction of different materials. In his honor, the group called its original 1987 instrument Eöt-Wash. The figure on page 19 shows its much-upgraded descendant, Eöt-Wash II, the rotating torsion pendulum with which the group is now testing the relative accelerations of miniature Earths and Moons toward the Sun. The original Eöt-Wash I, built in response to Ephraim Fischbach's provocative suggestion of a short-range force that mimics a small correction to gravity, did much to kill that so-called fifth force. (See PHYSICS TODAY, July 1988, page 21.)

Surrogate Earth and Moon

The four cylindrical 10-gram test bodies arrayed around the Eöt-Wash II torsion pendulum have identical dimensions and gold plating. But their different internal compositions are meant to provide surrogates of the Earth and Moon. "Because we don't want to restrict our results by any preconception of how a compositional anomaly might couple to gravity," explains Adelberger, "we use test masses that simply embody the known differences between Earth and Moon."

Their compositional difference is dominated by the difference between the Earth's mantle and its core. The two gray cylinders, representing the Earth's core, are made of iron, nickel, and chromium. The blue cylinders, representing the Moon (and the Earth's mantle), are mostly quartz (SiO_2), with some magnesium.

The four-cylinder array hangs like a little chandelier from a delicate fiber with a torsion constant of 0.03 ergs per radian of twist, yielding a free-oscillation period of about 15 minutes. Four right-angle mirrors are mounted on the pendulum between the test masses to reflect the laser beams that monitor the twist angle of the torsion fiber. The entire apparatus—fiber suspension and laser monitoring system—is continuously rotated on a laboratory turntable at a variable rate whose period is always set at some half-odd-integer multiple of the free oscillation period. One cannot completely suppress the pendulum's free oscillation. In the absence of any other perturbations, the oscillation would still exhibit thermal noise of order kT, corresponding to a torsion amplitude of a few microradians.

What the Seattle experimenters are looking for in their Fourier decomposition of the twist angle's time dependence is a diurnal component that tracks the moving Sun, indicative of a differential acceleration of the test masses that violates the weak equivalence principle. On the other hand, signal components precisely at the instrument's rotation frequency, without regard to the Sun, are indicative of perturbation sources fixed in the laboratory frame—for example, magnetic fields, the instrument's tilt, and the local gravity gradient.

There are, unfortunately, spurious diurnal effects that perturb this delicate apparatus: Cars fill up and vacate the parking lot, and the Sun sequentially warms different slopes of the local hillside. Both these effects vary the building's tilt ever so slightly. Electric power use wanes after working hours. Happily, the man-made diurnal effects follow the 24-hour calendar day, which differs seasonally from the actual solar day by a few seconds. Over several months the two get out of phase by as much as 15 minutes. That helps the group filter out anthropogenic perturbations.

Atom Interferometer Measures g with Same Accuracy as Optical Devices

The acceleration due to gravity, g, can be measured simply by timing how long it takes an object to fall. One can accomplish this with great precision by orienting an optical interferometer so that one of its arms is vertical. If the mirror in that arm is then allowed to fall part way, a Doppler shift in the reflected light signals its rate of fall. A similar measurement can now be done just as accurately with falling atoms (whose atomic frequencies are Doppler shifted), thanks to a long-term effort by a group at Stanford University. Achim Peters, Keng Yeow Chung, and Steven Chu recently reported[1] that their atom interferometer has determined g to within three parts per billion.

The increased accuracy allowed the Stanford team to test whether an atom falls at exactly the same rate as a macroscopic body. In a modern version of Galileo's classic experiment, the Stanford group "dropped" atoms in their interferometer and compared the acceleration to that of mirrors in a commercial optical interferometer taken into the same lab. The two measurements agreed to within seven parts in a billion, confirming the equivalence principle in the quantum regime (see the story on page 19).

Whereas an optical interferometer controls light beams with mirrors, the atom interferometer built at Stanford manipulates atoms with pulses of light. The experimenters began with a cooled and trapped cloud of atoms, and launched it vertically upward, like water in a fountain. A combination of three laser pulses put the atoms in a superposition of two hyperfine ground states, sent them along two different spatial paths, and recombined them at the detector. Because the wavefunctions evolved differently along the two paths, a net phase shift—which depends on g—was introduced when the atoms interacted with the laser pulses. The value of g was deduced from the resulting interference fringes. Such gravitationally-induced quantum interference was first observed in neutron interferometry nearly 25 years ago.[2,3]

It was no small feat to eliminate the many sources of error needed to achieve parts-per-billion accuracies. Chu and his coworkers developed a design that is relatively insensitive to drifts of the lasers and incorporated an actively stabilized vibration-isolation system. Furthermore, they have corrected for a vertical gradient in g and for changes in g caused by ocean tides. The biggest systematic effect is the uncertainty in the correction due to Earth's rotation.

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