Closing In On Einstein's Special Relativity Theory

With exquisitely precise measurements not possible even a few years ago, physicists are testing the theory explicitly

FOR A THEORY THAT STANDS AS ONE OF the great triumphs of modern science, Einstein's special theory of relativity had until recently never stood on a completely firm experimental footing—the few explicit tests were only accurate enough to guarantee the formulas of special relativity to within about 2%. But over the past 11 years, physicists using instruments undreamed of in Einstein's time have finally fixed that. With such tools as extremely stable lasers, physicists have now improved the experimental verification of special relativity by a factor of 4000.

"Of course, in a sense, special relativity had already been well tested because it's at the core of all of modern physics," notes Clifford Will, a physicist at Washington University in St. Louis. Quantum electrodynamics, for instance, includes special relativity in its framework and makes predictions that agree with experiment to a dozen decimal places.

Nevertheless, the verification is comforting—especially for nonphysicists, who sometimes seem to find it difficult to swallow the peculiar predictions of special relativity. The notion that the speed of light does not depend on the motion of the observer, for instance, seems to contradict common sense. Anyone who has ridden a bicycle knows that the relative speed of a head wind increases as you pedal faster into it. And other consequences of Einstein's theory, which says that time and space are relative, are equally strange: A clock that moves at a high speed past an observer will appear to run more slowly, and a fast-moving measuring stick will appear to shrink.

Historically, Einstein was pointed toward his special theory by an experiment performed by Albert Michelson and Edward Morley in 1887. At the time, scientists believed that light traveled in an invisible substance called the ether, which permeated all space; light beams would travel at a fixed velocity in the ether, but they would seem slower or faster to an observer moving with respect to the ether, depending on whether the observer was moving in the same direction as the light or against it.

Michelson and Morley set out to determine how fast the earth was moving through the ether—and got an unexpected result. Their experiment used a system of mirrors to split a light beam into two parts traveling perpendicular to each other and then to recombine the two beams so that they would produce an interference pattern. The researchers reasoned that the earth's motion through the ether should change the observed speeds of the two beams in different ways and influence how they interfered with each other. By rotating their apparatus through 90°, Michelson and Morley expected these velocity shifts to produce a change in the interference pattern that they could use to calculate the earth's speed through the ether.

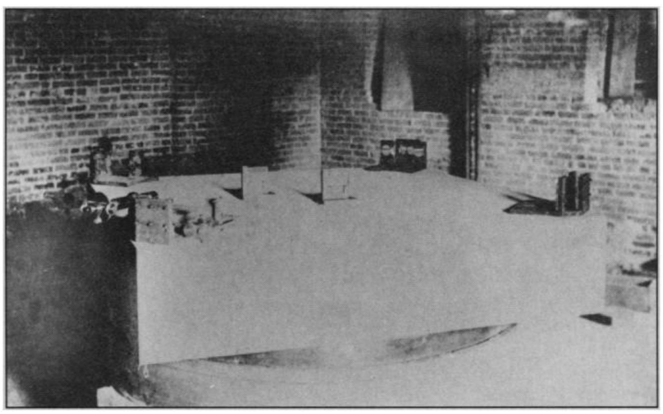
But the interference patterns didn't change, no matter which way the two scientists turned their apparatus. This implied that the speed of light was the same in every direction—and threw into question the whole concept of the ether.

Eighteen years later, Einstein developed his special theory of relativity, which explained the Michelson-Morley result. But Einstein, depending mostly on his own intuition about how the universe behaved, jumped way ahead of the existing data, and it wasn't until the 1930s that two important confirming experiments were performed.

The Kennedy-Thorndike experiment of 1932 used equipment much like Michelson and Morley's to show that the speed of light in a moving system is independent of the velocity of that system. When linked with its predecessor's conclusion that the speed of light was the same in all directions, this implied that the speed of light is always constant, regardless of its direction or the motion of an observer. In 1938, the Ives-Stillwell experiment measured the frequency of light emitted from fast-moving hydrogen atoms to demonstrate the phenomenon of time dilation—a moving clock seems to go more slowly by a factor of $(1-v^2/c^2)^{-1/2}$, where c is the speed of light and v is the speed of the clock with respect to the observer.

Theoretical physicist H. P. Robertson of Caltech put the finishing touches on the proof in 1949. In a seminal paper, he showed that if certain reasonable assumptions were made about how the universe behaves, then the validity of special relativity could be confirmed from the two 1930s tests plus the Michelson-Morley experiment. However, although all three tests were marvels of experimental technique at the time they were done, their precision was not high by today's standards. The Kennedy-Thorndike experiment, the least accurate, had an uncertainty of 2%. The new age of experimental verification of special relativity did not begin until 1979.

In that year, John Hall and Alain Brillet of the Joint Institute of Laboratory Astrophysics in Boulder, Colorado, performed a modern version of the Michelson-Morely experiment, taking advantage of very stable lasers to get a precision 4000 times greater than that of the original. "Ours used an optical interference condition like Michelson-Morley," Hall says, but there the similarity ends. Instead of mirrors and primitive light sources, the two physicists used two carefully tuned and very stable lasers. And instead of an interference pattern, they measured the two lasers' "optical heterodyne beat"—a technical characteristic related to the difference between the frequencies of the two lasers.



No ether. *The original Michelson-Morley apparatus, with mirrors and beam splitters.*

Original at the Mount Wilson and Los Campanos Observatories

Despite these differences, the two experiments actually test the same physical phenomenon, Will explains. Both are looking for the presence of a "preferred reference frame" that would serve as a privileged backdrop for the physical workings of nature; in Michelson and Morley's experiment it was the ether, and in Hall and Brillet's it was the cosmic microwave background of the universe. If special relativity were invalid, the outcome of an experiment would be dependent on its motion with respect to that preferred frame.

In their experiment, Hall and Brillet first fixed the frequencies of the two lasers and measured their optical heterodyne beat. They then rotated one of the lasers. As with the Michelson-Morley work, if the lasers moved with respect to some preferred frame, the frequencies of their light should depend on their velocity with respect to that frame. Rotating one laser would then shift that one's frequency but not the other's, thereby altering the beat between them. But Hall and Brillet, like Michelson and Morley, saw no evidence of motion with respect to a fixed reference frame.

Within the past 2 years researchers have also put the other two theoretical underpinnings of special relativity on a precise experimental footing. In 1985, a group of physicists at the University of Aarhus in Denmark and Colorado State University in Fort Collins used a beam of fast-moving neon atoms for a modern Ives-Stillwell test. When excited by a laser, neon atoms emit light at a precise frequency, so they can be used as clocks; by looking at the variation of the speed of these "clocks" as the Earth moves through space, the researchers measured the time dilation of special relativity to an accuracy of 40 parts per million.

Then in April of this year, Hall and coworker Dieter Hils put the third leg on the experimental tripod supporting special relativity with an updated Kennedy-Thorndike experiment. "This work allows [special relativity] to be deduced entirely from experiment at an accuracy of 70 parts per million," Hall says—a 300-fold improvement over the previous best. As in the 1979 Hall-Brillet study, the researchers measured the heterodyne beat between two lasers, but with a couple of changes. First, they didn't rotate either laser. Instead, they used two different types, taking advantage of the fact that if special relativity were invalid, the frequencies of the two lasers should change in different ways as their velocities with respect to a preferred reference frame changed. Second, they recorded the heterodyne beat over 24 hours.

As the Earth rotates, the velocity of the lab and the lasers changes with respect to the cosmic ray background. Then if the behavior of the lasers is dependent upon their velocity in this preferred reference frame, the two lasers should be affected differently, causing their heterodyne beat to shift over the 24-hour period. But to a high precision, the researchers saw no change. The experiment would have been impossible, Hall says, without the ability to keep the lasers' frequencies almost perfectly stable over several days—a feat that would have been unachievable only a few years ago.

And it just keeps getting better. "We could probably improve the accuracy [of the 1979 experiment] by a factor of 4000 now," Hall says. And the Aarhus researchers are expected to announce soon a result with a much more accurate measurement of time dilation. Where will it all stop? "At some point, it's not clear how much you gain [from continuing to test special relativity]," Will says. "I wouldn't necessarily spend millions of dollars to test it further," but as long as experimental advances make it easy to add the extra decimal point, it will probably keep going. ■ ROBERT POOL

Tilting at Einstein

While most modern scientists accept Einstein's special theory of relativity as gospel, a few "heretics" would like to bring down the church. Although these nonbelievers probably include more than a few cranks, they also include some serious scientists who have thought long and deeply about special relativity and find some of its tenets unacceptable. Recently, two of these dissidents have grabbed the attention of the relativity community with an unusual cash challenge.

Petr Beckmann, professor emeritus of electrical engineering at the University of Colorado, and Howard Hayden, a physicist at the University of Connecticut, will pay $2000 to the first person who offers a valid optical experiment proving that the speed of light on Earth is the same east-to-west as west-to-east, within 50 meters per second. The winner doesn't even have to have done the experiment personally. But the two iconoclasts think their money is safe. Because of practical constraints on laboratory experiments, Hayden notes, "You never measure the speed of light from point A to point B. You measure the round-trip speed." Physicists know the round-trip speed to within 1 meter per second, but the one-way speeds are much less certain.

And it is here that Beckmann and Hayden think they have found a chink in Einstein's armor. The special theory of relativity predicts that the speed of light is constant in all directions and to all observers regardless of their own velocities. But Beckmann thinks that's wrong.

Einstein's dictum holds that there are no preferred reference frames in nature—an axiom that implies such strange phenomena as length contraction and time dilation. "We reject the interpretation that Einstein gave when he elevated the observer from something that measures nature to something that influences nature," Beckmann says. In place of special relativity, Beckmann would institute a theory in which the dominant field in a system determines the preferred reference frame. Near Earth's surface, he says, that would be Earth's gravitational field.

That leads Beckmann to predict that the measured speeds of eastbound and westbound light differ by several hundred meters per second. He says that since Earth's gravitational field propagates outward at a finite velocity, the planet rotates inside the preferred frame defined by the gravitational field. Then if c represents the usual speed of light (and, in Beckmann's theory, the speed of light in the preferred frame), Beckmann predicts that the speed of light measured east-to-west will be the sum of c and Earth's rotational velocity; similarly, the west-to-east speed will be the difference between c and the rotational velocity. Beckmann points out that the usual tests of special relativity (see main story) assume that the preferred frame is the cosmic microwave background, and this, he says, has caused them to miss the effects of a preferred frame tied to Earth.

Meanwhile, Hayden is testing Beckmann's predictions with an experiment in which he suspends a charged capacitor in a shielded vacuum chamber. If the capacitor is indeed moving with respect to a preferred reference frame, that motion should result in a tiny torque that pushes the capacitor to align itself with its plates facing east and west. Hayden says that initial results seem to support Beckmann, but that he must reduce the noise level of his equipment to make sure he's getting a real signal.

Both Hayden and Beckmann realize that many of their colleagues may consider them cranks. "I refuse to have a grad student working on this project," Hayden says, "because I don't want to damn him to unemployment." But the lure of debunking the special relativity gospel is too strong for either researcher to give up now. ■ R.P.

ADDITIONAL READING

A. Brillet and J. Hall, "Improved laser test of the isotropy of space," *Phys. Rev. Lett.* **42**, 549 (1979).

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