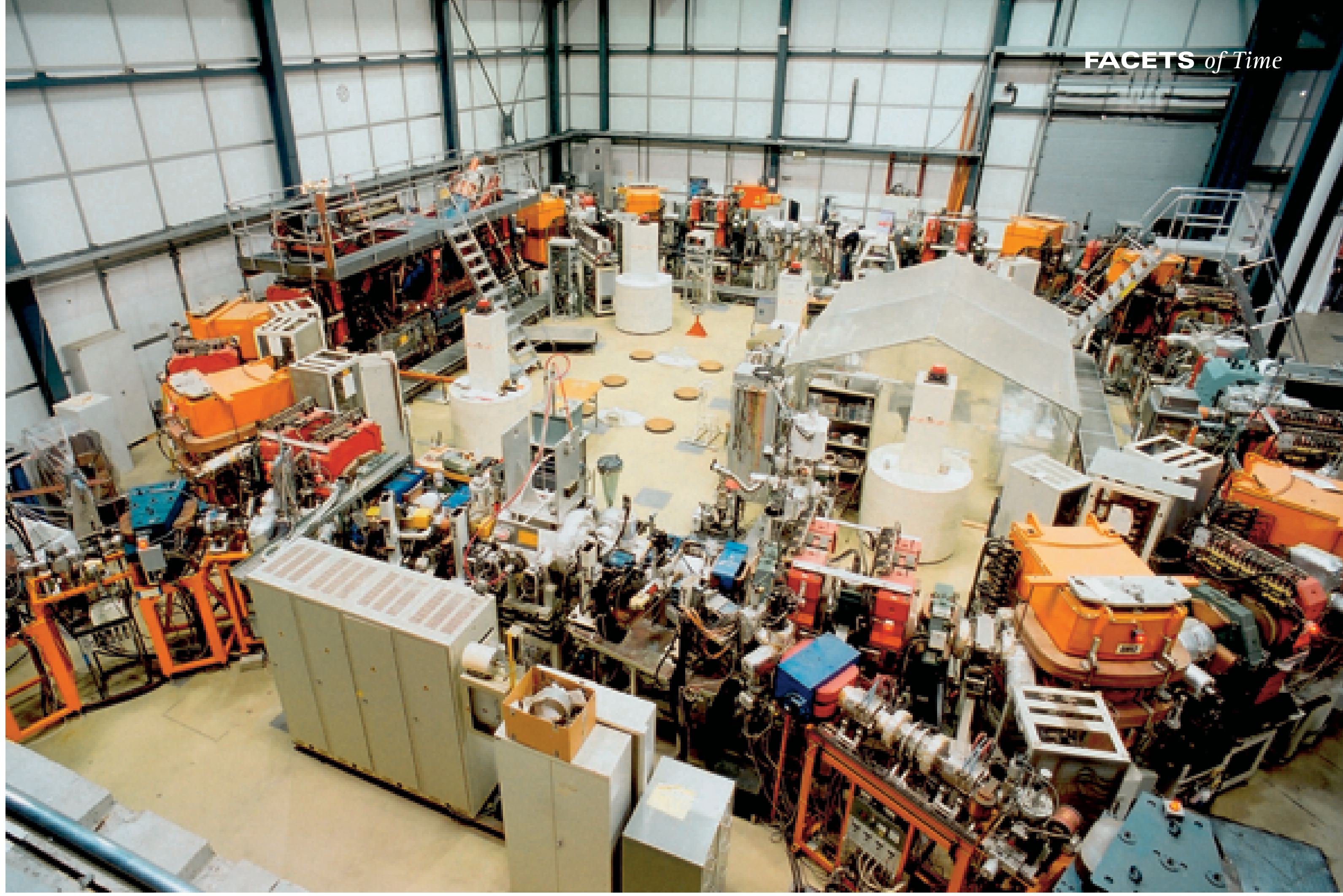
# Clocks Run More Slowly at the Racetrack

*A theory is valid only until it is disproved. And so, physicists have been testing Einstein's theory of relativity for nearly a hundred years – so far with no signs of weakness. A team of researchers led by* **Dirk Schwalm,** *Director at the* **Max Planck Institute for Nuclear Physics** *in Heidelberg, recently measured Einstein's postulated slowdown of time ("time dilation") with a level of precision never before attained. Their findings: the theory of relativity continues to be flawless.*



A "racetrack" for particles: In the Test Storage Ring in Heidelberg, lithium ions race at a speed of 19,000 kilometers per second. Researchers use this to measure the effect of time dilation.

Photos: MPI for Nuclear Physics

When Guido Saathoff and his Ph.D. candidate Sascha Reinhardt enter the cramped lab in the basement of the accelerator hall on Monday morning, they switch on their laser and check to see how it's doing. On bad days, the sensitive instrument is not stable enough and must be adjusted with a great deal of skill and know-how. It can easily take an entire morning before the two physicists get to tackle their actual project: verifying the special theory of relativity with greater precision than ever before.

Saathoff and Reinhardt measure what is probably the most astonishing prediction of the relativity theory: time dilation, which holds that time passes more slowly in a rapidly moving system than in a system that is at rest relative thereto. The two researchers test this phenomenon on the lithium ions whizzing about above their heads at 19,000 kilometers per second in a particle ring at the Max Planck Institute for Nuclear Physics. At this speed, which is 6.5 percent of the speed of light, the ions could circumnavigate the Earth in just over two seconds. According to Einstein, if they were equipped with particle clocks, the clocks would run about two-tenths of a percent slower than Guido Saathoff's wristwatch. And as odd as it sounds, this Heidelberg-based team was able to verify precisely this effect. The scientists' recently published work met with great interest around the globe.

## The "Magic Constant" of Modern Physics

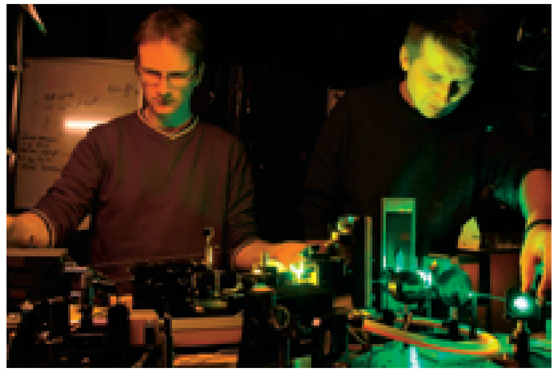
The origins of the Heidelberg experiment can be traced back to Einstein himself, who was the first to suggest a similar test of his special theory of relativity in 1907. That was two years after his so-called *annus mirabilis*, the "miracle year:" In 1905, when Einstein was 26 years old and employed at the patent office in Bern, Switzerland, he published three papers in three months, two of which would revolutionize physics. One of them described light as a particle current. This paper, which paved the way for the quantum theory, earned Albert Einstein the Nobel Prize for Physics in 1921; the second publication, On the Electrodynamics of Moving Bodies, the special theory of relativity, made him famous.

A core proposition of the special theory of relativity is that the speed of light always has the same value – 300,000 kilometers per second – regardless of the system in which one measures it. This contradicts what we have all experienced in everyday life. We need only sit in a car, drive down the left lane of the highway at 120 kilometers per hour and pass a truck traveling at 90 kilometers per hour. Both speeds might be measured, for example, by a radar gun on the side of the road. From our perspective, our car is not moving at all relative to us. After all, we are sitting firmly in our seats. At the same time, it is 30 kilometers per hour faster than the truck. Conversely, when measured from our standpoint, the same truck approaching us from the opposite direction would race past us at 210 kilometers per hour. Thus, the speeds are simply subtracted or added, depending on the direction of travel – at least, that is how Isaac Newton's classical physics envisaged it.

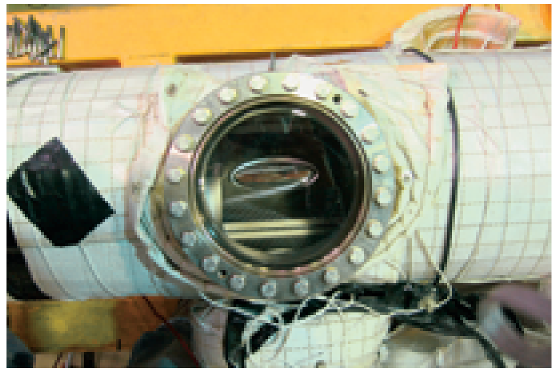
Pursuant to the special theory of relativity, this simple law no longer applies. Here, the relative speeds are calculated according to a complicated formula. The differences compared to the classical case multiply with increasing speed and, at the speed of light, result in a peculiar consequence: regardless of how quickly and from which direction one approaches a beam of light, it always moves at 300,000 kilometers per second. If we take this physical assumption to its logical conclusion, as Einstein did in 1905, time and space acquire completely new characteristics. One result is what is known as length contraction, which means that fast-moving bodies are shorter in the direction of movement than bodies at rest. Another is the equivalence of mass and energy, which is expressed by what is likely the most famous formula of all time, $E = mc^2$. The third prediction of the special theory of relativity relates to the time dilation mentioned above. Now, the constancy of the speed of light is, for the present, just a hypothesis. Einstein ventured it because, with it, he could solve problems that had arisen in the foundation of the basic physical theories of his day. That is why it was important to him that the predictions of his theory be confirmed by experiment. He knew that it would not work with normal clocks – detectable effects appear only at extremely high speeds.

## From Theory to Experiment

In 1907, Albert Einstein proposed a cunning experiment for measuring time dilation using atoms. He based it on an experiment that Johannes Stark had conducted a short time previously. (Ironically, it was Stark who distinguished himself in the 1920s as an absolute anti-relativist and a fervent advocate of "German



Teamwork: Guido Saathoff (left) from the Max Planck Institute for Nuclear Physics in Heidelberg and his colleague Sergej Karpuk from the University Mainz calibrate the lasers in their cramped lab.



Peering into the pipe: A window in the steel pipe of the Heidelberg storage ring allows the photometer to register the glowing ions.

physics.") In his lab at the University of Greifswald, Johannes Stark had accelerated positively charged atoms, so-called ions, in electrical fields, and examined them. These ions emit light of a very specific wavelength that can be measured exactly. If we imagine the light as an oscillating wave, we can also think of the oscillation duration (frequency) as a time metronome, or as Einstein writes: "We may consider such an ion as a clock of a certain frequency." This is the basis for today's atomic clocks.

Einstein's idea now was: If the ions fly very quickly in the canal rays, time goes more slowly for them than it does in the lab. The light they emit must thus oscillate more slowly, which should express itself in a longer wavelength and a shorter frequency. Back then, however, measurement precision was not sufficient to test the formula for the special theory of relativity. It wasn't until 1938 that two American physicists managed to do this, by measuring a spectral line of hydrogen moving in the form of a canal ray at about 1,500 kilometers per second. The measurements they obtained confirmed the theory of relativity to within an accuracy of approximately 2 percent.

Since then, this historic experiment has been repeated numerous times with increasing precision and with various measurement methods. So far, all results have confirmed the special theory of relativity. So do we really even need to make any further attempts? Must we not by now assume that Einstein's theory is correct? "You can never conclusively prove that a theory is right," says Guido Saathoff. "It is valid only until an experimental result contradicts it."

## A COOL BATH IN A SEA OF ELECTRONS

The special theory of relativity has withstood all attacks for 99 years now, but there are some very good reasons why researchers continue to search for a gap. Theoretical physicists have long been searching for a theory that combines gravity (Einstein's general theory of relativity) and the atomic forces (quantum theory) in a single, primitive force. These efforts have not yet met with success, although several attempts have been made to achieve the "grand unification." Some of them predict that the special theory of relativity is not entirely accurate. "There haven't been any quantitative predictions about the order of magnitude in which we might expect to find a discrepancy," says Saathoff, commenting on the current state of things, "but even the smallest indication would give the theory a great boost."

At the Max Planck Institute in Heidelberg, the tests of the special theory of relativity have been in progress since as early as the end of the 1980s, when the Test Storage Ring was set up there. The idea for this came from Gerhard Huber, Professor at the Institute of Physics at the University Mainz. One of the physicists from his group continues to collaborate on the experiment. The storage ring is similar to a racetrack, 55 meters in circumference, on which magnets hold charged particles in their lanes – in Saathoff's experiment, positively charged lithium ions that are produced in a neighboring building. There, they are brought up to their final speed of 19,000 kilometers per second in the strong electrical fields of a tandem accelerator before they enter the storage ring. As soon as a few million particles populate the ring, it is closed off to additional ions because, before the experiment begins, the researchers must optimize the circulating ion beam – and that is the experiment's success.

At first, the lithium ions still have very different speeds. The physicists refer to this as a "hot" beam. They cool it down by causing the ions to fly through "cold" electrons in one section of the ring. Cold means that the speeds of the electrons, on average, now deviate very little from the target speed. When the lithium beam passes through the electron bath, the particles collide and impact each other with their electric forces. Consequently, ions that are too fast are slowed down and ions that are too slow are accelerated. The lithium beam shoots through the sea of electrons some 345,000 times per second, and after about five seconds, the differences in speed are sufficiently balanced out so that measuring can begin.

In principle, one could now define the lab frequency that a laser must have in order to excite the moving ions to glow and to compare them with the light frequency of the resting ions. However, the method is too imprecise, as the particles still do not all have exactly the same speed, even following the extensive bath in the electron sea: the "clocks" run at different speeds.

A further problem is the classic Doppler effect, which makes a wave's frequency appear higher when an observer moves toward it, and lower when the observer moves away from it. In everyday life, we know this from acoustic waves: the siren of a passing fire truck first sounds higher, and then lower than the actual tone (and that perceived by the driver). This Doppler effect overlaps with the time dilation and prevents a simple precision measurement.

The Heidelberg physicists solve both of these problems by firing two laser beams into the storage ring. One runs precisely parallel to the ion beam, and the other runs counter to it. The frequencies of these two lasers are adjusted such that they excite ions with a specific speed to glow. In effect, they pick out two different speed classes. A photo detector peering laterally into the steel tube measures the light yield of the two groups.

## EINSTEIN IS STILL RIGHT TO WITHIN A MILLIONTH

Now, if the frequency of one of the lasers is varied until it excites the same ions as the other laser, the light yield will decrease, because now only one speed class glows: the two lasers have to share the ions traveling at this speed. In the experiment, the light yield suddenly drops in this situation – and this can be measured very accurately. Fortunately, what happens now is that the Doppler effects of the anti-parallel laser beams are perfectly cancelled out at this point and only the frequency shift of the theory of relativity remains. Astonishingly, the measurement result then no longer depends on the speed of the ions. Now the physicists must compare the measured light frequency of the orbiting lithium ions with that of resting ions.

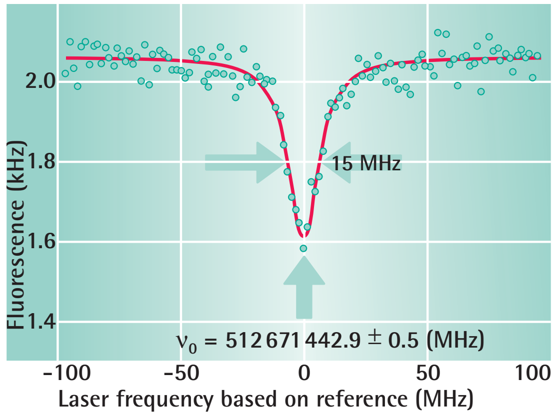
In this way, Guido Saathoff and his colleagues succeeded in confirming Einstein's formula for time dilation to within an accuracy of less than a millionth. This is a ten-thousand-fold improvement over the original experiment of 1938. And it appears that the Heidelberg scientists still have not entirely exhausted their possibilities. "At present, the precision of our figure is limited, not by our measurements, but by the knowledge of the frequency emitted by the lithium ion in the lab, in other words, the precision with which the resting clock runs," says Sascha Reinhardt. That is why he intends to address the problem in his dissertation.

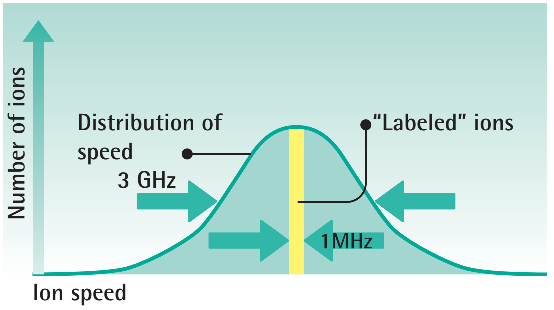
Since the resting frequency is also measured with a laser, it will be necessary to calibrate this laser. As is so often the case in physics, instruments are calibrated to a well-known standard that is measured as precisely as possible. The lasers used in the Einstein experiment, for example, are based on a specific light frequency that is emitted by iodine atoms. To calibrate the laser even more exactly, Reinhardt will travel with them to Garching. At the Max Planck Institute for Quantum Optics located there, Theodor Hänsch's research group operates a so-called frequency comb that can be used to measure the iodine emission with the utmost precision.

When the Heidelberg team has exhausted the capabilities of its equipment, perhaps by the end of the year, it can increase the accuracy of its measurement by another fivefold. Then the researchers will have to pursue other avenues, and one of them may lead to the Society for Heavy Ion Research (GSI) in Darmstadt. There, ions could be brought up to greater speeds than in the Heidelberg accelerator. The effect of time dilation would be more pronounced and could thus be measured more accurately. "This would allow us to achieve 10 times greater precision," says Sascha Reinhardt. Will the theory of relativity then show the first signs of weakness, a hundred years after Einstein's "miracle year?"

THOMAS BÜHRKE

ILLUSTRATIONS: ROHRER





The lithium ions move at various speeds, indicated by the green bell curve. Here, the lasers mark off a narrow region. When both lasers have exactly the same frequency (yellow line), the intensity of the light emitted by the ions drops (above).

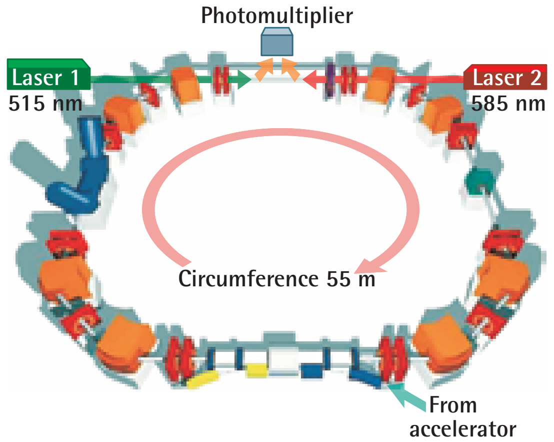


Diagram of the Heidelberg Test Storage Ring, into which physicists fire two opposing laser beams, exciting the ions to glow.