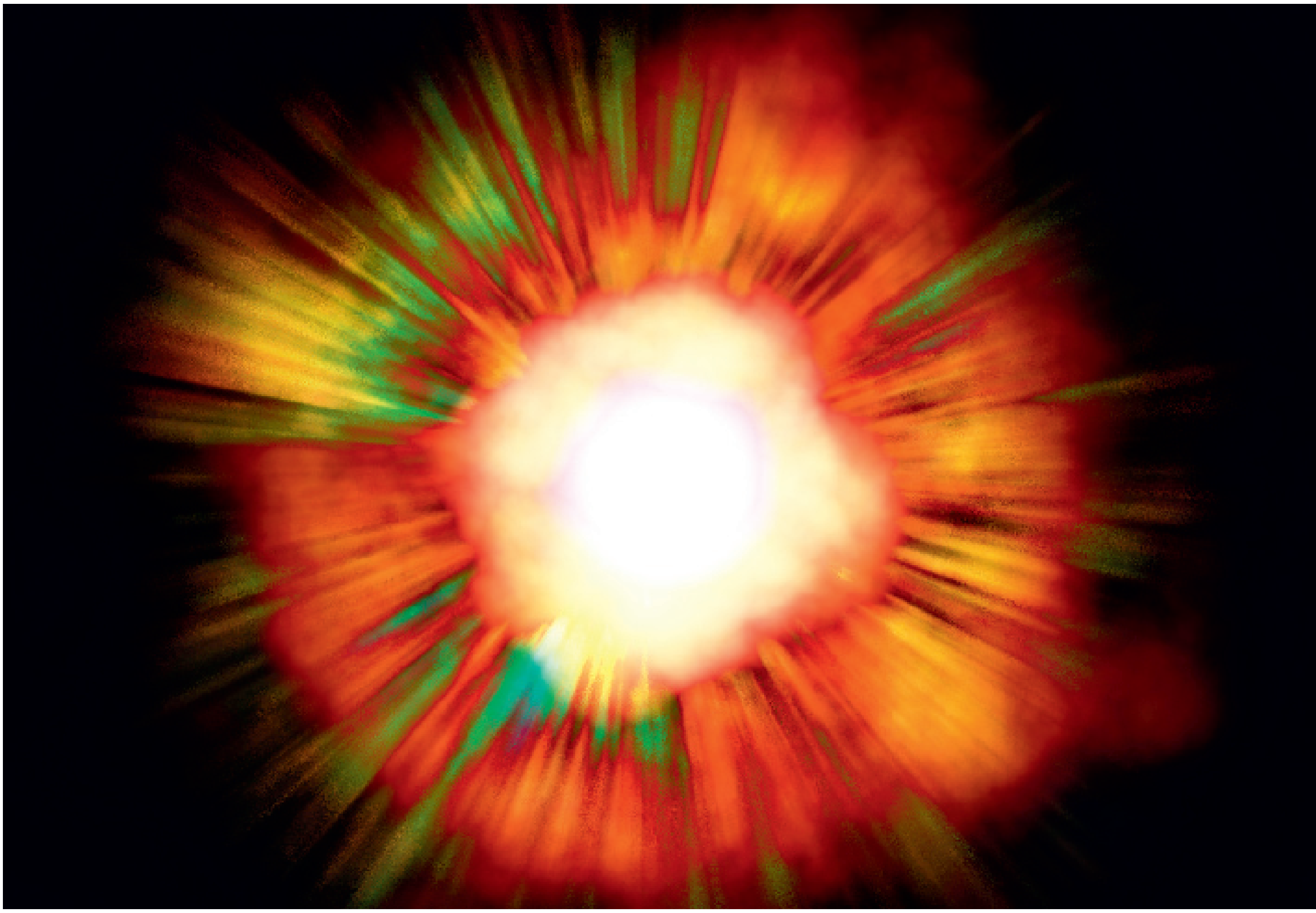


What Makes Up the **Cosmos**

Nature shuns perfect symmetry. If it didn't, the universe would contain no matter – only radiation. For half a century now, physicists have been searching for the reason behind this minor yet, for humans, essential departure from perfection. Three Nobel Prizes have already been awarded for partial successes, the last one in 2008. At the **MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS** *in Heidelberg,* **MICHAEL SCHMELLING** *and* **ALBAN KELLERBAUER** *are investigating this phenomenon by studying the properties of matter and antimatter particles.*

PHOTO: SPL – AGENTUR FOCUS

When the philosopher René Descartes was contemplating the existence of man, he concluded: "I think, therefore I am." For decades, physicists have pondered why anything exists at all. A satisfactory answer has yet to be found, but they have devised some new experiments to probe the question more deeply in the coming years.

The – literally existential – question follows from relativistic quantum field theory, which states that for every particle there is an antiparticle. Both partners have largely the same properties, such as identical mass, but opposite charge. So an antiproton, for example, is just as heavy as the positively charged proton and has an electrical charge of precisely the same magnitude, but negative – at least according to today's standard theory. If the two come into contact, they are annihilated, and matter and antimatter are fully transformed into energy. Based on the numbers alone, the annihilation of one kilogram of matter could supply all the energy needed to run a city of one million inhabitants for an entire year.

This self-destructive behavior must have played a key role in the evolution of the early universe. In the first billionths of a second after the Big Bang, the extremely hot universe was filled with radiation and matter. Particle-antiparticle annihilation was going on continually; and conversely, such pairs formed out of radiation. In the end, there should have been just as much matter as antimatter. However, numerous observations have convinced the astrophysicists that, in the observable part of the universe, there is no antimatter left over from the Big Bang.

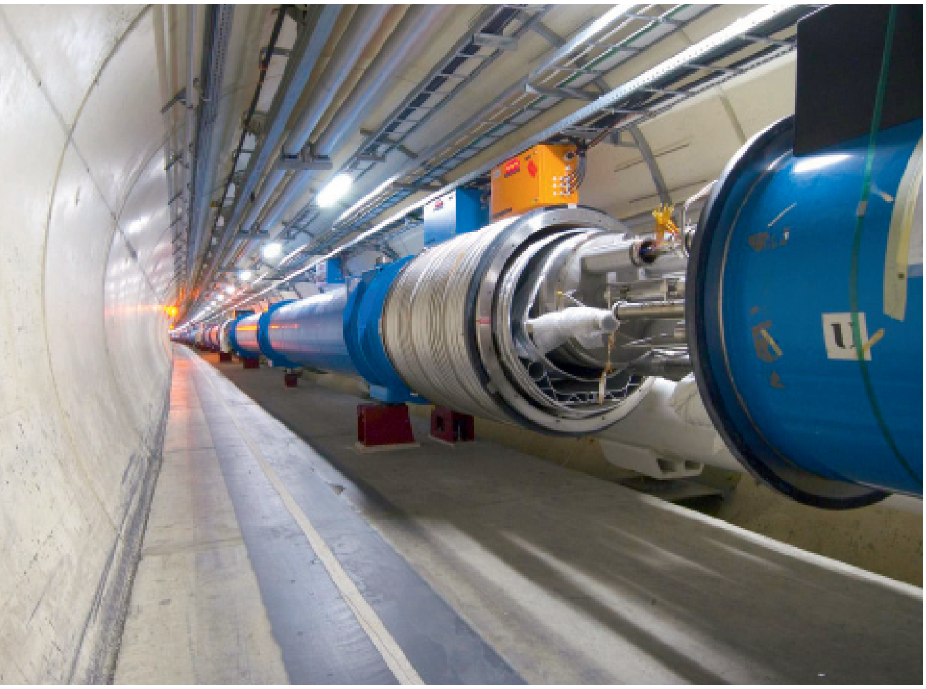
From this, the researchers conclude that there must have been a tiny imbalance during this early phase of the universe: for every few billion matter-antimatter pairs that were annihilated, one particle must have been left over. That is akin to all men and women living on the Earth getting married on the same day and one person being left alone. This difference seems to be minor, but it cannot be explained with a purely random surplus.

A SYMMETRY THAT ISN'T PERFECT

We owe our existence to this tiny deviation from perfect symmetry between matter and antimatter. The question of why nature appears to slightly favor the one type of matter is what occupies Michael Schmelling and Alban Kellerbauer from the Max Planck Institute for Nuclear Physics in Heidelberg.

This put Schmelling on the trail of an experiment that American physicists James Cronin and Val Fitch conducted at a particle accelerator at Brookhaven National Laboratory in 1964. The particle collisions that took place there created, among other things, so-called neutral K mesons. Like almost all elementary particles, these decay after a short time.

There are two types of neutral K mesons, with the primary difference between the two being their lifetimes. Both are composite states of quarks and antiquarks, but the short-lived type decays primarily into two pions, while the long-lived one decays into three pions. These decays are mediated by the weak force, one of the four fundamental interactions. In one of these, an asymmetry between matter and antimatter must occur, and based on everything par-



In the Large Hadron Collider (LHC), protons are fired at each other with such high energy that reactions such as those that prevailed shortly after the Big Bang can be studied. Ideal conditions for studying the asymmetry between matter and antimatter.

PHOTO: CERN

Photo: MPI for Nuclear Physics

Key parts of the LHCb detector were built under clean-room conditions at the MPI for Nuclear Physics.

ticle physicists know today, this can only be the weak force.

If there were perfect symmetry between particles and antiparticles, it would be absolutely forbidden for long-lived particles to decay into two pions. Or in the language of particle physics: the CP quantum number would be conserved. To the physicists' surprise, however, this was not the case. Cronin and Fitch noticed that a small fraction of the long-lived K mesons decay into two pions. So the CP symmetry is not exact, and there is a fundamental difference between matter and antimatter.

"At the time, that was a real surprise for the physicists," says Schmelling. But they quickly recovered from it and integrated this so-called CP violation into the emerging Standard Model of elementary particles. Toshihide Maskawa, Makoto Kobayashi and Yoichiro Nambu were recently awarded the Nobel Prize in Physics for this extension. Cronin and Fitch had already received this Prize in 1978.

The next important step came three years after this memorable experiment. The famous Russian physicist Andrei Sakharov published an article in which he showed that this symmetry breaking between matter and antimatter is needed to explain an excess of matter in the young universe. According to Sakharov's theory, the universe also must have gone through a state of thermal non-equilibrium less than a billionth of a second after the Big Bang. "One can perhaps imagine this as a phase transition, similar to when water freezes and becomes ice," explains Michael Schmelling. "Here, the asymmetry was essentially frozen and the matter dominance of the universe established." Did that provide the final answer to this fundamental question?

No! As theoreticians soon realized, the asymmetry measured in the K meson decays was much too small. "It would have to be a billion times larger in order to explain the greater amount of matter over antimatter," says Schmelling. Nevertheless, many physicists are convinced that one key to this mystery lies in CP violation.

Theory predicts that CP asymmetries depend on the particle type. Relatives of the K mesons, the B mesons, are particularly interesting in this respect, since they are expected to display much larger decay asymmetries than the K mesons. For that reason, physicists have already been studying the decay of these particles for years at two accelerators in the US and Japan. One problem is that B mesons are much heavier than K mesons. Producing them in particle collisions thus requires significantly more energy. In addition, only a small fraction of all possible decays is suitable for measuring CP violation. So the field is still wide open.

NEW PARTICLES – BORN FROM FIREBALLS

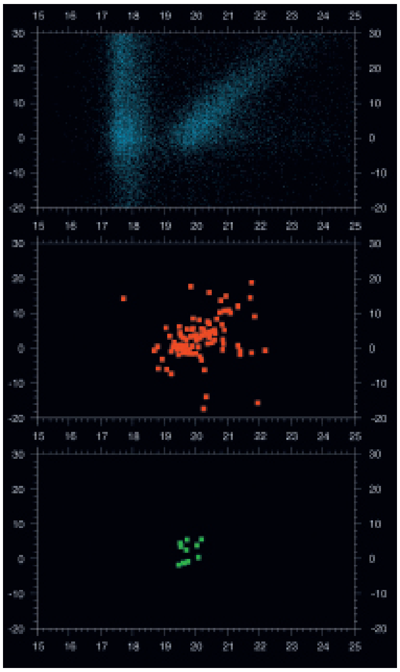
This is where the new super-accelerator, the Large Hadron Collider (LHC), of the European particle laboratory CERN comes into play. Protons will be fired at each other with extremely high energy in the 27-kilometer-long ring accelerator. New particles, including the desired B mesons, will form in the resulting "fireballs."

The expected production rate at the LHC is a dream for Michael Schmelling and his colleagues: "In this accelerator, there will be several thousand times more B mesons created every second than in the same amount of time at the other accelerators." Schmelling's group is part of an international collaboration of some 600 physicists who built one of the four large LHC detectors: LHCb. Although the production rate of these particles will be very high, the researchers have a difficult task ahead of them: The B mesons are not produced in isolation,

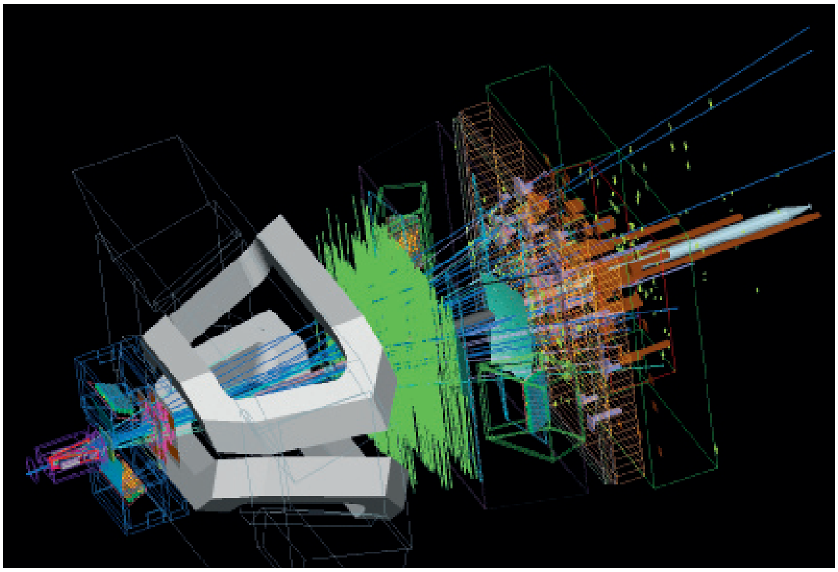
Witnesses of the inverted world: In 1995, researchers at CERN succeeded in producing antihydrogen. The "fingerprints" on the computer monitor testify to this; the lower portion (green) shows 11 events whose radiation corresponds exactly to the radiation created when electrons and positrons are annihilated.

but rather together with dozens of other particles. Furthermore, only about one in ten thousand B meson decays is interesting for later analysis. At the same time, the researchers must fight a background of around ten million "normal" proton-proton collisions per second – for although numerous particles are produced here, not one of them is a B meson. So it is the proverbial search for a needle in a haystack.

Of course Schmelling and his colleagues were disappointed when, due to a technical defect, the accelerator had to be shut down again shortly after it was started. The LHC, which was cooled down to just a few degrees above absolute zero, will not be able to be started up again until summer 2009. "We could have gathered a lot of useful data even during the start-up phase," says the Heidelberg-based Max Planck physicist. Just as with small lab experiments, the researchers must also gain experience with a huge and complex detector like LHCb. Here, too, there will be parts of the detector with different strengths and weaknesses. "We will have to take this into account when analyzing the data."



Photos: MPI for Nuclear Physics (above) / SPL - Agentur Focus (below)



The particle collisions of interest to the researchers can be simulated in advance using computers.

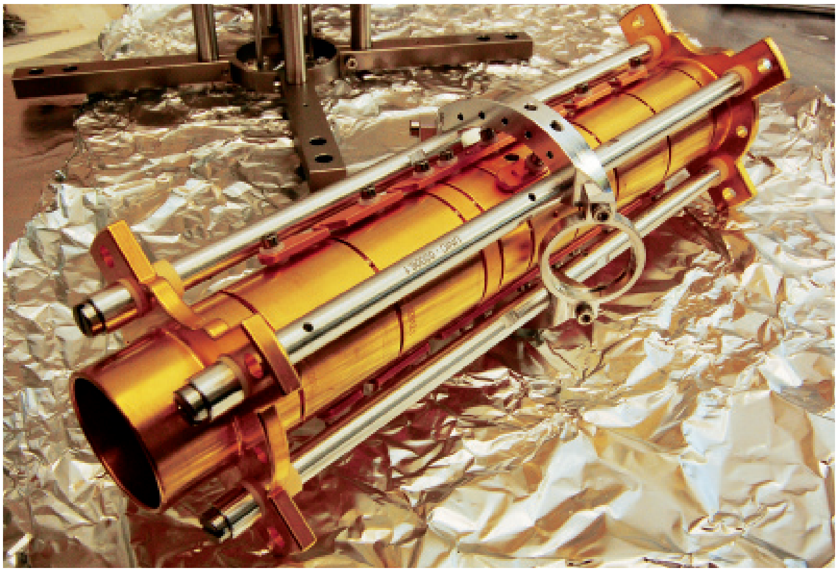
With a length of 20 meters and a diameter of 10 meters, LHCb is the size of a three-story house and weighs a total of 4,500 tons. The apparatus consists of several different sub-detectors whose task is to measure the properties of the particles created in the high-energy collisions: momentum, charge and mass. Schmelling's group began to develop silicon strip detectors and corresponding readout chips for the LHCb experiment ten years ago.

ELEVEN-SQUARE-METER SILICON DETECTORS

On one surface – measuring about the size of four packs of cigarettes – the lab model of a silicon detector has 384 strips and 3 readout chips. It gives only a weak impression of the complete system built into LHCb. There, it covers a total active surface of approximately 11 square meters, and has more than 272,000 readout channels. With strip spacing of 0.18 millimeters, the passage of a charged particle can be reconstructed at 16 detector positions with a precision of 0.05 millimeters.

The researchers encountered a number of problems in developing the approximately 30-square-millimeter readout chips. Each chip integrates 128 extremely sensitive pre-amplifiers with which the weak signals of a silicon strip detector can be read out at a rate of 40 MHz and stored for 4 millionths of a second. During that time, an independent logic determines whether the signals belong to a potentially interesting proton-proton collision. If so, then the information is passed on. Furthermore, the chips must be able to withstand the intense radiation at LHC for a long time. "Any normal electronics components would be destroyed within a few hours," says Schmelling.

The research and development work of the group in Heidelberg was shared between experienced postdocs and students – with four doctoral dissertations having been successfully completed over the past few years, and three currently still in progress. ►



The cylindrical Penning trap, where the antiparticles are stored.

When the LHC is restarted in summer, the Heidelberg-based physicists hope to harvest the fruits of their ten long years of work. Then they will use specially developed computer programs to filter the data for interesting decays of the B and anti-B mesons, and measure CP asymmetries with the greatest possible precision. The most exciting result for them would be to find deviations from theoretical predictions based on the Standard Model. That would be a clear indication of a “new physics,” such as the existence of as-yet-unknown elementary particles that influence the decay of the mesons and that may have helped matter prevail over antimatter in the early universe.

The LHC offers the particle physicists entirely new opportunities, and their expectations are high. “We hope that someday we will understand all processes so well that we can answer the question of why there is matter in the universe,” says Michael Schmelling.

So the physicists will use the experiments with the LHCb detector to observe decays in which there is known to be an asymmetry between matter and antimatter. One of Schmelling’s colleagues at the institute, Alban Kellerbauer, is taking another, more radical approach. He wonders whether particles and antiparticles might perhaps have slightly different properties after all. For example, the current Standard Model states that protons and antiprotons have exactly the same mass and a charge of equal magnitude but opposite sign. But is that really the case? And if not, how might minor differences be measured?

For about ten years now, physicists have been trying to generate antihydrogen atoms to compare their properties with those of hydrogen atoms – an extremely difficult task. The constituents of the antiatoms, antiprotons and antielectrons (positrons) can be created relatively easily, but combining them to form an atom is particularly tricky.

Nevertheless, this goal seems to be very promising, as hardly any other value in quantum physics can be measured as precisely as a certain transition of an electron in the hydrogen atom. The group of physics Nobel laureate Theodor Hänsch from the Max Planck Institute of Quantum Optics used lasers to determine this number down to 14 decimal places. It seems only natural to measure the same transition in the antihydrogen atom and compare it with Hänsch’s figure. So laser spectroscopy of antihydrogen was the goal of the two research groups Atrap and Athena at CERN. Alban Kellerbauer was part of the Athena group and is only too familiar with the hurdles these experiments present.

First, antiprotons were created in an accelerator. Since they were moving at nearly the speed of light, they were first slowed down in a particle decelerator (actually an accelerator run in reverse) and then fired through a metal foil, which further reduced their energy to a thousandth of the original value. The antiprotons were now slow enough to be transferred into a so-called Penning trap. That is a metal container inside of which a combination electrical and magnetic field confines the antiprotons.

At the same time, positrons that had been created in the decay of radioactive sodium-22 were introduced into this trap. Cleverly shaping the electrical field made it possible to trap these tiny clouds of antiprotons and positrons and to superpose them. In the process, the particles joined to form antihydrogen atoms.

The two groups at CERN first accomplished this feat in 2002. In the

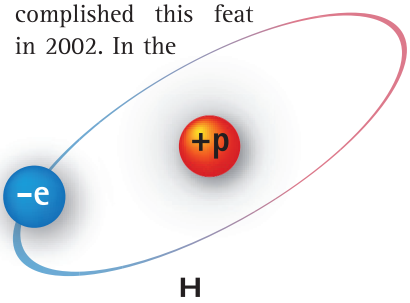
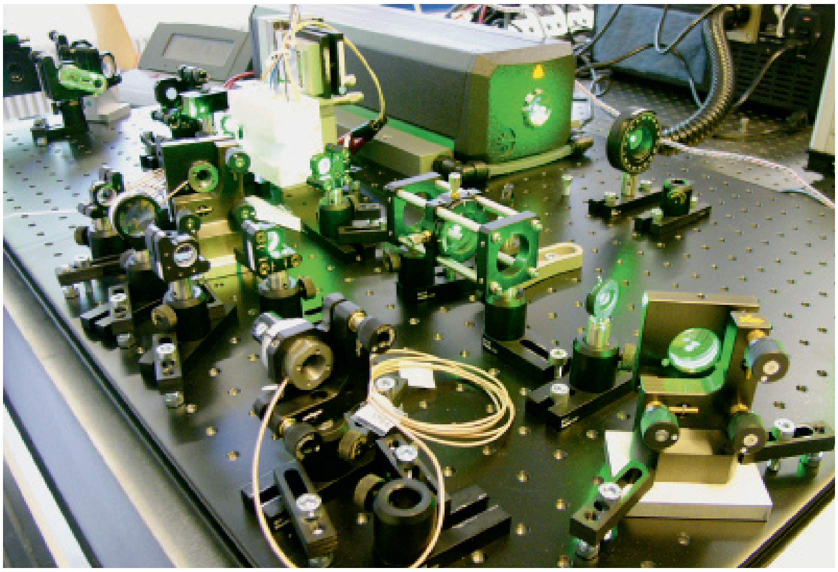


Illustration: Christoph Schneider / Photo: MPI for Nuclear Physics

two years that followed, together they produced several million antihydrogen atoms, and yet the ambitious goal of the laser analysis was not attained. This was because the electrical fields in the Penning trap can confine only electrically charged particles. But as soon as an antihydrogen atom forms, it is neutral and is no longer affected by the fields. It dashes out of the trap and disintegrates on the container material after just fractions of a second.

But the situation is not entirely hopeless. It is, in fact, possible to build an additional trap comprising inhomogeneous magnetic fields that can hold the antihydrogen atoms. Unfortunately, the particles coming out of the Penning trap are too fast for this. “The magnetic trap can be pictured as a pot into which one tosses the atoms like balls,” is how Alban Kellerbauer explains the technology. “But the balls are so fast that they bounce right back out.” Since the magnitude of the magnetic field cannot be increased arbitrarily, the physicists are facing a real problem at the moment.



Laser beams are used to slow down the antiparticles. This technique is being tested in lab experiments.

The Athena and Atrap groups are currently refining their equipment, but Alban Kellerbauer is very skeptical that it will really be possible to produce enough antihydrogen for laser spectroscopy in the foreseeable future. He therefore set up, together with colleagues from several other European universities, a separate group called Aegis, with which he aims to address a very different issue: Does antimatter fall in exactly the same way as matter in Earth’s gravitational field? A cornerstone of modern physics states that all objects fall at the same rate regardless of their mass and chemical composition. This applies only in a vacuum, where there is no friction to impair their movement. But it has never been possible to test this fundamental law for antimatter.

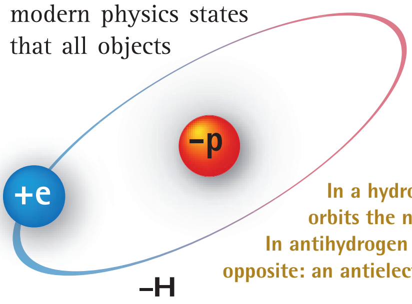
The End of the General Theory of Relativity?

In modern approaches to a new framework of particle physics, such as string theory, it seems to be possible that matter and antimatter could fall at different rates of acceleration. “But string theory does not make any concrete prediction,” says Kellerbauer. It would be sensational if his group were to detect such a difference. “It would be the end of the general theory of relativity,” Kellerbauer adds. But how does one measure the fall of antihydrogen atoms?

Instead of capturing the antiatoms after they form, they are accelerated parallel to the Earth’s surface. This beam then travels over a distance of about one meter, bending a few micrometers downward before striking a detector. An intricate measuring apparatus known as an interferometer makes it possible to determine the exact vertical distance of this fall. The experimental value obtained in this way is then compared with the expected value. If the antihydrogen beam lands on the detector somewhat higher or lower than expected, it means that antimatter falls at a different rate than matter in the gravitational field.

The Aegis project had already received a positive review from the Scientific Committee at CERN. Now the Research Board has also given it a green light, so Kellerbauer’s group can set up the equipment and begin with the measurements in two to three years. If the researchers should detect a difference between matter and antimatter, they would be pushing the door wide open for a “new physics.” And they would be a big step closer to answering the question of why there is now matter in the universe.

Thomas Bührke



In a hydrogen atom (far left), an electron orbits the nucleus, which consists of a proton. In antihydrogen (left), the charges are just the opposite: an antielectron (positron) orbits the antiproton.

Illustration: Christoph Schneider / Photo: MPI for Nuclear Physics