Why Antimatter Matters

ALBAN KELLERBAUER

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany.
E-mail: a.kellerbauer@cern.ch

Almost ten years after the first production of cold antimatter at CERN, the confinement of antihydrogen has recently been achieved for the first time. Several experiments installed at the Antiproton Decelerator intend to test the symmetry between matter and antimatter by means of trapped anti-atoms. In addition, in the coming years it is planned to study the effect of gravity on antiparticles for the first time. Meanwhile, evidence from the Large Hadron Collider hinting at a violation of charge–parity symmetry beyond the Standard Model of particle physics has yet to be confirmed. A violation of the discrete symmetries that describe the relation between matter and antimatter could explain the excess of ordinary matter in the Universe.

Introduction

As Richard Feynman once jokingly advised,[1] if you meet a Martian and he holds out his *left* hand in greeting, beware: he could be made of antimatter! In that case, caution should in fact be taken, because when antimatter comes into contact with ordinary matter, enormous amounts of energy are released. This process is called annihilation. According to the equivalence of energy and matter, postulated by Albert Einstein, an annihilation releases more energy than any other chemical or physical process. According to the well-known formula

$$E = mc^2 \tag{1}$$

the annihilation of one half gram of antimatter, for instance, produces more energy than the explosion of the Hiroshima nuclear bomb. But how likely is it that distant stars and planets made from antimatter exist; that we might one day face an extra-terrestrial who offers us his left hand?

We have been holding a preliminary answer to this important question for about 15 years: in June 1998 the AMS-01 experiment (Alpha Magnetic Spectrometer) was taken into an Earth orbit aboard space shuttle Discovery and was operated for 100 hours. The aim of the AMS collaboration, led by Samuel Ting, was to search for atomic nuclei made from antimatter. The lightest representative of this species is the
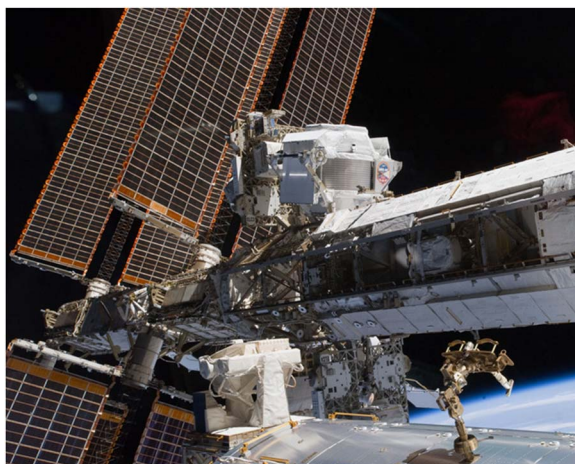
Figure 1. Photograph of the Alpha Magnetic Spectrometer AMS-02 on board the International Space Station, slightly above the centre of the image. (Photo: NASA.)

antiproton ($\overline{p}$), the nucleus of the antihydrogen atom ($\overline{\text{H}}$), where a bar over the particle symbol designates an antiparticle. It is created when highly energetic cosmic radiation passes through the interstellar medium. These are called secondary antimatter particles. Heavier nuclei, such as antihelium, are a different affair. They are now only created by nuclear fusion in a sun – in the case of antihelium in an anti-sun. Such antiparticles are called primary antimatter. The AMS-01 experiment detected a total of almost three million helium nuclei, but not a single antihelium nucleus.[2]

After a development time of more than ten years, the AMS-02 experiments came into operation in an Earth orbit in May 2011 (Figure 1). AMS-02 is an updated version of its predecessor designed for permanent operation on board the international space station ISS. The detector has a total mass of more than 6.7 tons and consists of six modules. These allow the determination of the velocity, charge, energy and spatial orientation of charged and neutral particles which traverse them. A star tracker continuously checks the position of the apparatus relative to the fixed stars. The main aim of AMS-02 is to detect about a thousand times more atomic nuclei than AMS-01. Thanks to this increased sensitivity, it can expand the search for antimatter suns up to the limits of the expanding Universe. Furthermore, the device is also able to detect the hypothetical neutralino and strangelet particles. Both are hot candidates for Dark Matter, which is assumed to account for a large part of the matter of the Universe without being visible to astronomical instruments.

Where is the Antimatter?

The result of the AMS-01 experiment suggests that there is no primary antimatter left in the present Universe. And yet precisely equal quantities of matter and antimatter should have been produced in the Big Bang about 13.8 million years ago. However,
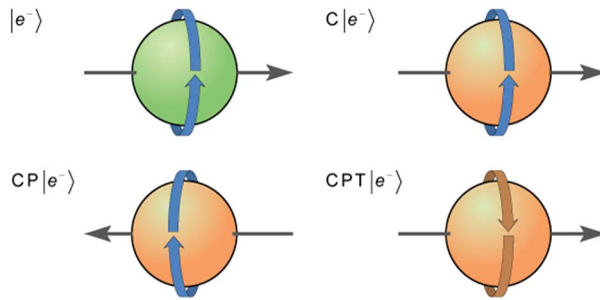
Figure 2. CPT theorem. From left to right and top to bottom: The successive application of the operators C (charge conjugation), P (parity) und T (time reversal) transforms an electron into a positron. The horizontal arrows designate the particle momentum, the circular arrows its spin.

the vast majority of the antimatter produced annihilated with matter in the ensuing fraction of a second, forming photons. This is the origin of the cosmic microwave background radiation. Surprisingly, a tiny part of ordinary matter remained after this gigantic explosion. Earth, and our solar system – even the entire visible Universe – are made up of this minuscule fraction. This imbalance is called baryon asymmetry, because baryonic matter is commonly considered as a representative for all types of matter. (Baryons are particles consisting of three quarks, the fundamental elementary particles that form atomic nuclei and other compound particles.) The imbalance between antimatter and ordinary matter is one of the great unsolved puzzles of modern physics.

Flashback. In 1930, British physicist Paul Dirac realized that his quantum mechanical wave equation for the electron, which was later to be named after him, also had negative-energy solutions. Instead of simply disregarding these solutions as 'unphysical,' he postulated the existence of particles with negative energy, whose properties exactly match those of normal particles;[3] only the signs of some fundamental properties, such as electric charge, would be exactly reversed. A few years later the antiparticle of the electron, the positron, was detected in cosmic radiation. Today we know that each of the familiar elementary particles has an antimatter partner. This consonance of matter and antimatter is closely linked to the discrete symmetries C (charge conjugation), P (parity or spatial inversion) and T (time reversal). They play an important role in quantum mechanics.

The CPT theorem, posited by Wolfgang Pauli in 1955, states that the laws of physics remain unchanged when a system is subjected sequentially to the operators C, P and T.[4] The proof of this postulate rests on a number of fundamental premises, which are nowadays part of the Standard Model. Pauli furthermore assumed that the laws are described by a quantum field theory. As we will see later, this condition is currently not met by gravity. It is an important consequence of the CPT theorem that by applying the combined operation CPT to a matter particle, its antimatter partner is obtained, and vice versa. These operations are illustrated in Figure 2 using the example of an electron, which is transformed into a positron by CPT. Initially,

physicists had assumed that each of the operations C, P and T applied separately also left the physical laws unchanged. However, this assumption quickly turned out to be false.

Violated Symmetries

In 1956, in the course of a thorough review of the scientific literature, Chinese-American theorists Tsung-Dao Lee und Chen-Ning Yang realized that the conservation of parity symmetry by the weak interaction had never been tested experimentally – in contrast to the electromagnetic and the strong forces. Only a few months later, experimental physicist Chien-Shiung Wu, also of Chinese origin, managed to conduct such an experiment. At the centre of the setup was a sample of the radioactive metal ^{60}Co, which decays into the stable nuclide ^{60}Ni by emission of an electron and an antineutrino with a half-life of 5.27 years. Wu first cooled the material to 10 millikelvin and aligned the nuclear spin of the atoms to a preferred direction by means of an external magnetic field (polarization). Afterwards she used scintillators to observe the direction of the momentum of electrons released in the beta decay.

Let us first consider the significance of the experiment. The nuclear spin, like any other angular momentum, is the cross product of a position vector and a momentum vector. If the operator P is applied to the atomic nucleus, the signs of both basis vectors are reversed, whereas the magnitude and the orientation of the nuclear spin remain unchanged. The situation is different for the momentum of the emitted electrons, which reverses its direction under spatial inversion. If parity symmetry were conserved in beta decay, precisely the same number of electrons (on average) should be emitted in the direction of the nuclear spin as in the opposite direction, because otherwise the decay process would differ from its mirror image. Yet Wu indeed observed a large degree of correlation between the polarization of the cobalt nuclei and the momenta of the emitted electrons. In this way she proved that the weak interaction violates parity symmetry.[5] The same year (1957), Yang and Lee – but not Wu – received the Nobel Prize in Physics.

Subsequently, it was supposed that at least the combined CP symmetry was conserved by all interactions. In the wake of the surprising discovery of P violation, quite soon the CP symmetry of weak decay processes was also scrutinized. In 1964, American physicists James Cronin and Val Fitch studied the decay of the neutral kaons $K^0 = d\overline{s}$ and their antiparticles $\overline{K}^0 = s\overline{d}$, which consist of pairs of down (d) and strange (s) quarks and their antiquarks. These short-lived kaons, which can be artificially produced only in an accelerator, usually decay into two or three pions. They can only decay via the weak force, because it is the only interaction that can change a particle's quark type (flavour). By a combination of several such processes, K^0 and $\overline{K}^0$ can even transform into each other. In this way a mixing of quantum states can take place, resulting in the formation of states K_1 und K_2. These are eigenstates of the CP transformation, i.e., they are left unchanged (up to a sign) under CP.

If we initially assume that the decay of neutral kaons conserves CP symmetry, the state K_1 should only decay into two pions, whereas K_2 should only decay into three pions. Because of the lower decay energy, the second reaction proceeds much more slowly than the first. Indeed, two populations with half-lives of 9.0×10^{-11} s and 5.1×10^{-8} s are observed in the decay of neutral kaons. The experiment of Cronin and Fitch consisted of verifying the identity of the long-lived kaons with the state K_2. For this purpose, they first let a beam of neutral kaons traverse a 15 m long flight path in order to select the long-lived component. Afterwards they searched the decay products for events with only two pions. Indeed they observed that about 0.2% of the long-lived kaons decayed in this way.[6] Thus, it had been demonstrated that the weak interaction also violates CP symmetry. In today's Standard Model, CP violation is incorporated by means of the so-called quark mixing matrix.

As in the case of the kaons, a mixing of quark eigenstates is also observed in the B and D mesons. In 2001, the experiments BaBar (SLAC National Accelerator Laboratory, USA) and Belle (KEK, Japan) almost simultaneously found a CP violation in the decay of the neutral B meson. The measurements were in agreement with the results from K decay and with the quark mixing formalism. The situation appears to be different for the newest results from the Large Hadron Collider (LHC) at CERN. At an accelerator conference that took place in the fall of 2011, members of the LHCb experiment led by Pierluigi Campana announced that there is mounting evidence for a strong CP violation in the decay of the D meson $D^0 = c\bar{u}$ (c – charm quark, u – up quark). The scientists studied particle collisions in which pairs of D and anti-D mesons had been formed. By means of the LHCb detector, which is more than 10 m tall and 20 m long, they then identified decays of these short-lived particles into final states containing either two pions or two kaons, each CP eigenstates with an eigenvalue of +1.

A possible CP violation would manifest itself by a difference between the decay probabilities of the initial particles D^0 and $\overline{D}^0$ into these states. Over the past 15 years, comparable measurements at other accelerators did not show any deviations beyond their experimental uncertainties. The LHCb collaboration measured the probabilities for all four possible decays. But instead of considering the differences in the decay rates of D^0 and $\overline{D}^0$ particles into pions and the corresponding quantity for kaons separately, the scientists subtracted the two differences. In this way they were able to minimize systematic errors. In the course of these measurements, they found an asymmetry of 0.8%, about a factor of ten larger than the CP violation predicted by the quark mixing matrix of the Standard Model.[7] For the time being, the results are based on about half the data from 2011. The results have a statistical significance of 3.5σ; this means that the observed asymmetry is non-zero with a probability greater than 99.7%. If this observation were corroborated, it would be a clear indication of new physics outside the Standard Model. However, the LHCb results have so far not been confirmed and can therefore not yet been considered as positive proof.[8]

The observed violations of the discrete symmetries are relevant for our initial question. In the middle of the 1960s, Soviet physicist and future Nobel Prize laureate Andrei Sakharov studied the reason behind the observed dominance of ordinary

baryonic matter. He realized that baryon asymmetry could have arisen immediately after the Big Bang during a period of thermal non-equilibrium. In addition to the obvious non-conservation of baryon number, this scenario would have required the violation of both C and CP symmetry.[9] The CP violation experimentally observed in kaon decay was however much too weak to be responsible for baryon asymmetry. It was realized only 30 years later that the matter–antimatter imbalance could also have come about by a violation of CPT symmetry in connection with a non-conservation of baryon number.[10] However, it remains to be determined which of the two processes is the dominant one.

A violation of CPT symmetry is inconceivable within the current Standard Model of particle physics. However, recent theoretical advances, which pursue a unification of the fundamental interactions into a 'Theory of Everything,' call into question some of the premises on which the CPT theorem is based. Take superstring theory, for example: In this approach, the principle of locality (the prohibition against action-at-a-distance) is no longer valid at the smallest length scales – and this contradicts Pauli's CPT theorem, which only applies to local and causal theories. It is possible to test CPT symmetry by comparing the properties of antiparticles with those of their ordinary-matter partners and looking for deviations. Over the past few decades a large number of such measurements have been carried out. In this way, for instance, the *g* factors (i.e. the magnetic moments) of the electron and the positron have been compared to a relative precision of 2×10^{-12} and the masses of the proton and the antiproton to 9×10^{-11}. Until now, no evidence of CPT violation has been found in any of these experiments.

Antihydrogen in a Trap

With a relative uncertainty of 4×10^{-15}, the transition frequency between the ground state (1S) and the metastable excited state (2S) of the hydrogen atom is currently the most precisely known physical quantity.[11] The measurements by the group of Theodor Hänsch are based on so-called Doppler-free spectroscopy, in which two photons impinging on the atom from opposite directions collectively contribute to the excitation. In this way, the shift of the transition frequency due to the thermal motion of the atoms (the Doppler effect) is reduced. The measured frequency is related to a caesium atomic clock by means of a frequency comb. It would stand to reason to perform the same measurement on antihydrogen in order to test CPT symmetry with the highest possible precision. For this reason the production of antihydrogen from its constituents, antiprotons and positrons, has been fervently pursued since the beginning of the 1990s. However, there is no primary antimatter in the Universe. So how can it be produced in order to examine it in the laboratory?

Again, the key lies in the equivalence of energy and matter. Pairs of matter and antimatter particles can be created from a large amount of energy. For this purpose, highly energetic protons are fired onto a metallic target, giving rise to pairs of protons and antiprotons. The antiprotons are selected with a magnetic filter and are then injected into the Antiproton Decelerator (AD), a storage ring with a circumference of

190 m. In the AD, they first circulate near the speed of light before being decelerated to an energy of 5 MeV within about 100 s by inverted accelerator cavities. Simultaneously, the beam is radially cooled and collimated. Afterwards, bunches containing roughly 3×10^7 antiprotons are distributed to the antimatter experiments located at the AD.

In 2002, scientists working on the ATHENA experiment headed by Rolf Landua managed for the first time to create cold antihydrogen in an ion trap.[12] For this purpose, they captured the antiprotons delivered by the AD in a Penning trap and further decelerated them to a few kelvin. Then they brought them into contact with equally cold positrons from a radioactive source. In this way, antihydrogen atoms spontaneously formed but, due to the fact that they are electrically neutral, they no longer remained confined. When these particles impinged on the trap electrodes, they gave rise to a characteristic annihilation signal, by means of which it was possible to elegantly demonstrate the formation of antihydrogen. At the same time, however, the created anti-atoms were lost for further measurements. Thus, the ATRAP and ALPHA collaborations further enhanced their apparatuses such that they allowed the capture and study of neutral antihydrogen.

In 2011, ALPHA, one of the successor experiments of ATHENA, announced that they had for the first time succeeded in the capture of antihydrogen. How was this achieved? A Penning trap is needed to confine the constituents, antiprotons and positrons. It consists of a homogeneous magnetic field along the trap axis and an electrical quadrupole field, which is applied to the cylindrical trap electrodes. The neutral antihydrogen atom is confined in a magnetic trap. The gradient of an inhomogeneous magnetic field B exerts a force

$$\mathbf{F} = \pm \mu \nabla B \tag{2}$$

on the magnetic moment μ of the atom. In the ground state the magnetic moment has the magnitude of the Bohr magneton

$$\mu = \mu_{\mathrm{B}} = \frac{e\hbar}{2m_{\mathrm{e}}} \tag{3}$$

where e and m_e designate the charge and the mass of the electron and $\hbar$ is Planck's constant. The sign of the direction of the force – towards the minimum or the maximum of the magnetic field – depends on the (arbitrary) alignment of the positron spin relative to the external magnetic field. Therefore, in the best of cases half of the atoms are trapped.

The difficulty lies in combining the two types of traps in such a way that their fields do not disturb each other. The radial component of the magnetic trap is problematic, in particular, because it breaks the cylindrical symmetry of the Penning trap. This can compromise the storage time of the ions. The problem is alleviated by the fact that ALPHA uses a radial trap with a high multipole order, because in this way the field magnitude rapidly decreases towards the trap axis. The trap configuration used by ALPHA is shown in Figure 3(a). The radial trap consists of so-called race track coils (red in the figure), which create an octupole field with a magnitude of about 1.7 tesla. Two circular mirror coils (green) ensure the confinement in axial direction.

(a)

(b)
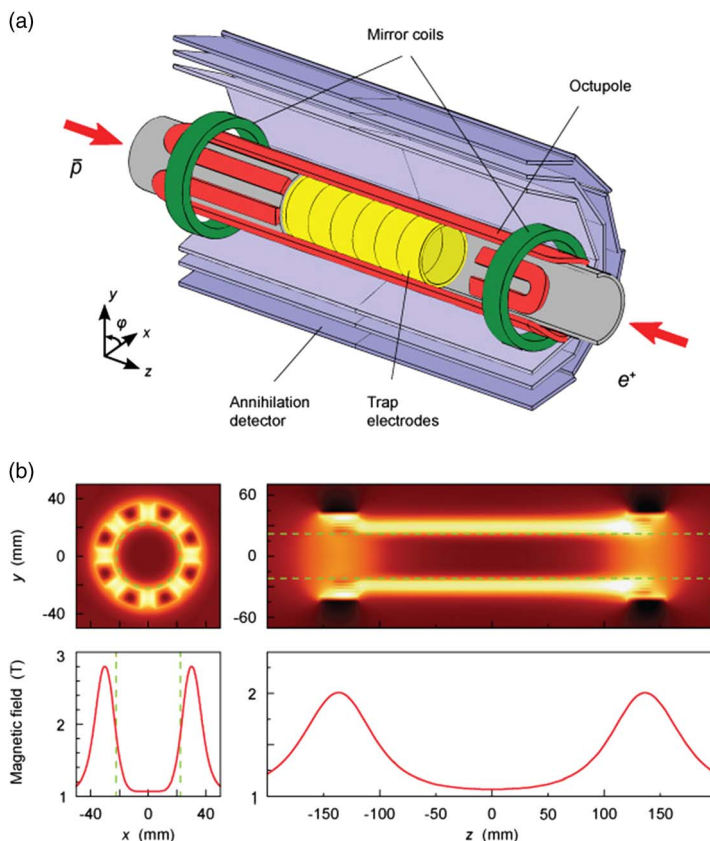
Figure 3. Combined ion and atom trap. (a) Configuration of the magnet coils and electrodes of ALPHA's combined ion and atom trap: Octupole coils (red), mirror coils (green), trap electrodes (yellow). The solenoid used to generate the strong axial magnetic field is not shown. (b) False-colour image of the magnetic-field magnitude in the radial and axial projection (top) and on the axis (bottom) as a function of the radial and axial coordinates. (Images: (a) CERN, (b) courtesy Nature Publishing Group.)

The solenoid magnet (not shown in the figure) has a field of 1 T. This results in a magnetic trap depth of just under 1 T, which corresponds to 0.6 K in temperature units (Figure 3(b)).

In summer 2011, ALPHA managed to store single antihydrogen atoms in the magnetic trap for many hundreds of seconds.[13,14] As was the case in ATHENA, antiprotons and positrons were confined in a nested electric potential (Figure 4). Their temperature is a few 10 K. The two clouds of particles are brought into overlap by a weak high-frequency excitation of the antiprotons, such that antihydrogen is spontaneously produced. A small part of the antihydrogen atoms, those whose temperature is below 0.6 K, remains trapped in the magnetic trap. After waiting up to 1000 s, the magnetic field of the octupole coils is ramped down within a few hundredths of a second. The anti-atoms then leave the trap and annihilate on
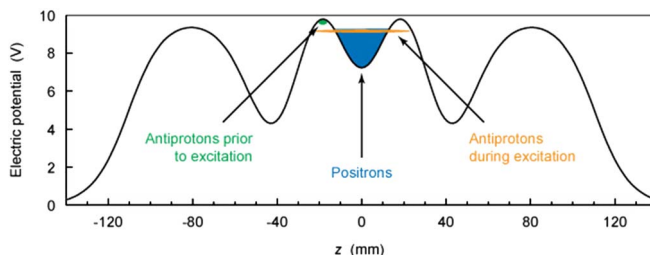
Figure 4. Ions in the Penning trap. Nested electric potential applied to the trap electrodes for the simultaneous confinement of positively charged positrons and negatively charged antiprotons in the Penning trap. (Image: CERN.)

the electrodes. This signal is recorded with a silicon strip detector, which surrounds the entire trap in three layers (light blue in Figure 3(a)). The storage of neutral antihydrogen has thus been demonstrated.

In a further experiment, the ALPHA group even managed to take a first step towards antihydrogen spectroscopy: by means of a microwave signal, the scientists changed the alignment of the positron's spin within antihydrogen with respect to the external magnetic field.[15] This caused the direction of the force due to the magnetic trap to be reversed for these particles and they were thus accelerated out of the trap. The observed correlation between the familiar annihilation signal with the resonant microwave excitation demonstrates that the hyperfine structure of antihydrogen coincides at least roughly with that of hydrogen.

Does the Anti-apple Fall Up?

The AEGIS group headed by Michael Doser, which is another successor of the ATHENA collaboration, is pursuing a completely different approach. As mentioned before, gravity is a special case among the interactions. It is the only one not described by a quantum field theory. Within General Relativity, gravity is a geometric phenomenon. Test bodies move along geodesics, the shortest paths between two points in four-dimensional spacetime. Matter causes spacetime to become distorted. The Weak Equivalence Principle (WEP), which states that all bodies fall with the same acceleration independent of their composition, directly follows from this notion. For bodies consisting of ordinary matter, measurements have confirmed the WEP to high precision. In a hypothetical quantum theory of gravity, however, both negative mass charges and exotic gravitons are conceivable, which could both result in a deviation from the equivalence principle for antimatter.

The principle of the AEGIS experiment is to study the deviation of a horizontal antihydrogen beam in the gravitational field of the earth.[16] Figure 5 shows an overview sketch of the apparatus. For the creation of antihydrogen, AEGIS makes use of a charge exchange reaction via the detour of positronium (Ps):

$$\mathrm{Ps} + \bar{p} \rightarrow \overline{\mathrm{H}} + e^- \tag{4}$$
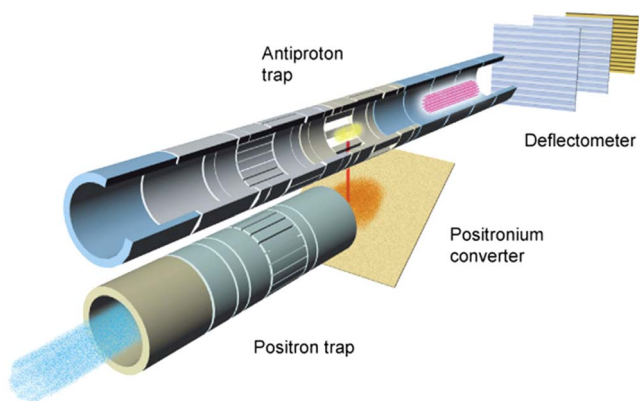
Figure 5. Principle of the AEGIS experiment (overview sketch). Antiprotons and positrons are stored in two parallel Penning traps within the same magnet. Positrons are converted into positronium in a nanoporous material. The positronium atoms pass through the pre-cooled antiprotons (yellow cloud), and cold antihydrogen is formed (pink cloud). The antihydrogen atoms are accelerated by means of an inhomogeneous electric field in the direction of the deflectometer, where the gravity measurement takes place. (Image: courtesy of Asimmetrie/INFN.)

Positronium is the bound state of an electron and a positron and has a structure very similar to that of the hydrogen atom. It can be produced with high efficiency from the bombardment of a nanoporous material with positrons. The advantage of this reaction is the fact that the formed antihydrogen has the same temperature as the pre-cooled antiprotons from which it was made. A low temperature is crucial for the measurement precision of the experiment. Afterwards, the antihydrogen atoms are accelerated into a beam by means of an inhomogeneous electric field. Its horizontal velocity v_{hor} is between 400 and 700 m s^{-1}.

The effect of gravity is determined via the vertical deflection of the beam over a flight path of about 80 cm. Assuming a local gravitation due to earth of $g = 9.81$ m s^{-2}, a shift of less than 0.01 mm is to be expected. Since the beam spot on the detector is much larger, such a small deviation cannot be measured directly. Therefore, AEGIS uses a measurement setup whose principle is loosely based on the matter wave interferometer developed by Ludwig Mach and Ludwig Zehnder. A Mach–Zehnder interferometer consists of three gratings with fine horizontal slits, mounted at equal distances L. As the beam passes through the first two gratings, a diffraction pattern is generated at the location of the third. The third grating functions as an analyser. A detector placed behind it records a maximal signal when the grating is brought into overlap with the interference pattern. Finally, the vertical displacement of the pattern is recorded as a function of the flight time.

However, at a temperature of 100 mK, the opening angle of the antihydrogen beam is larger than the expected diffraction angle. Furthermore, decoherence effects, for example atomic transitions or annihilations on the grating, can further wash out the diffraction pattern. For this reason, AEGIS makes use of a moiré deflectometer,

which is the classical counterpart of the Mach–Zehnder apparatus based on matter wave interference. Instead of diffraction maxima, the first two gratings cast a classical shadow pattern on the third one. Nevertheless, the vertical drop of the pattern is the same in both cases and amounts to

$$\delta x = -gT^2 \tag{5}$$

where $T = L/v_{\text{hor}}$ is the time of flight between a pair of gratings. The gravitational acceleration g is obtained from a fit of equation (5) to a large number of measurements with different beam velocities v_{hor}. Simulations have shown that about 10^5 antihydrogen atoms at a temperature of 100 mK are required to carry out a measurement of the earth's gravitational acceleration to a relative precision of 1%. Such a measurement would take a few weeks of beam time.

After more than ten years of research work, the experiments located at the Antiproton Decelerator have reached significant milestones towards precision measurements with antimatter. With the successful capture of neutral antihydrogen, all of the prerequisites for laser spectroscopy on antimatter atoms are now satisfied. The two collaborations ALPHA and ATRAP are in the process of modifying their apparatuses such that a laser beam can reach the confined particles. In this way, a first test of CPT symmetry in an atomic system is finally coming within reach. It will bring us closer to answering the question of whether the already established CP violation or a still hypothetical CPT violation is responsible for baryon asymmetry. Meanwhile, AEGIS is making great strides towards a test of the Weak Equivalence Principle with antimatter. However, some parts of the AEGIS experiment, in particular the moiré deflectometer, are still being developed. Therefore, first results should not be expected before the beginning of 2015.

References

1. R. Feynman (1964) Symmetry in physical laws. Lecture at Cornell University, Ithaca, New York, USA, 16 November. Available from youtube.com/watch?v=zQ6o1cDxV7o.
2. M. Aguilar *et al.* (2002) *Physics Reports*, **366**, p. 331.
3. P. A. M. Dirac (1931) Proceedings of the Royal Society, Series A, **133**, p. 60.
4. W. Pauli (ed.) (1955) *Niels Bohr and the Development of Physics* (New York: McGraw-Hill).
5. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes and R. P. Hudson (1957) *Physical Review*, **105**, p. 1413.
6. J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay (1964) *Physical Review Letters*, **13**, p. 138.
7. R. Aaij *et al.* (2012) *Physics Review Letters*, **108**, p. 111602.
8. S. Stahl (2013) Properties of b & c hadrons. 48es Rencontres de Moriond, La Thuile, Italy, 9–16 March 2013. http://moriond.in2p3.fr/QCD/2013/Tuesday Morning/Stahl.pdf.
9. A. D. Sakharov (1967) *Soviet Physics JETP*, **5**, p. 24.
10. O. Bertolami, D. Colladay, V. A. Kostelecký and R. Potting (1997) *Physics Letters B*, **395**, p. 178.

11. C. G. Parthey *et al.* (2011) *Physical Review Letters*, **107**, p. 203001.
12. M. Amoretti *et al.* (2002) *Nature*, **419**, p. 456.
13. G. B. Andresen *et al.* (2010) *Nature*, **468**, p. 673.
14. G. B. Andresen *et al.* (2011) *Nature Physics*, **7**, p. 558.
15. C. Amole *et al.* (2012) *Nature*, **483**, p. 439.
16. A. Kellerbauer *et al.* (2008) *Nuclear Instruments and Methods in Physics Section B*, **266**, p. 351.

About the Author

Alban Kellerbauer gained a PhD in Nuclear Physics in 2002 in Heidelberg. He completed his Post-doc at CERN, working at ISOLDE and with the antimatter experiment ATHENA. From 2006 to 2011 he was head of an Emmy Noether junior research group at the Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg. In 2007 he was a founding member of the AEGIS collaboration. Habilitation 2009 in Heidelberg. Since 2011 he has been research group leader at MPIK and grant holder of an ERC Consolidator Grant. He is a founding member of the Young Academy of Europe.