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ANTIHYDROGEN–TESTBENCH FOR THE SYMMETRY OF THE ANTIWORLD*

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Comprising an antiproton and a positron, antihydrogen is the simplest atom of antimatter. The transition frequency of 2.466×10^{15} Hz from the 1S ground state to the 2S metastable state, if measured with the accuracy set by the natural line width of 1.1 Hz, offers the chance to test CPT invariance and the equivalence principle.

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1. The first antiatoms

Two years ago an experiment was performed at CERN to produce the world's first antiatoms. Using 2 GeV/c antiprotons routinely available in the Low Energy Antiproton Ring LEAR nine atoms of antihydrogen were created.

The experiment worked by squirting a jet of Xe droplets across LEAR's circulating antiproton beam. Occasionally, an antiproton colliding with a Xe atom produced an electron-positron pair in the Coulomb field of the nucleus. Even more rarely, the positron moved in exactly the right direction and with exactly the right velocity to attach itself to the ongoing antiproton, forming an atom of antihydrogen. Being neutral the antiatom was free of the grip of LEAR's bending magnets and flew off towards an external detector where its annihilation with matter was observed. The CERN press service announced the result as soon as the paper [1] had been accepted by Physics Letters and the news media immediately spread it around the world. Rzeczpospolita [2] reported it in their week-end edition of January 6, synchronously with the New York Times.

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Each of the nine atoms remained in existence for about 40 nanoseconds and travelled at nearly the speed of light from the point of creation to the detector. High precision spectroscopy, as we know it from normal hydrogen, however, is only possible if the antiatoms can be made to stand still for minutes or hours in a laser beam. In the new experiments currently being planned the ingredients for antihydrogen therefore will first be captured and slowed down to every-day speeds in electromagnetic traps which are cooled to a few tenths of a degree Kelvin. Then the antiproton and positron samples will be emptied into a reaction trap. Superimposed on this trap is a magnetic quadrupole field which has the capability to levitate the resulting neutral antiatoms. The goal is to compare the properties of antihydrogen with those of the standard atom, hydrogen.

2. Hydrogen and antihydrogen

The hydrogen atom is the simplest atom we know. Its nucleus is a positively charged proton which essentially represents the total mass of the atom. Encircling the proton is a negatively charged electron. The atom is held together by the attractive electric force between the positive and negative charges. Quantum effects arising from the uncertainty principle keep the two particles at a distance and define the size of the atom.

The recipe for antihydrogen is equally simple. Now the nucleus is a negatively charged antiproton and the shell contains a positron. Here a fundamental symmetry of our world comes into play. For each particle there exists an antiparticle and the antiworld, properly defined to include static as well as dynamic properties of the fundamental building blocks, should be indistinguishable from the normal matter world. Antihydrogen is as stable as hydrogen. The most spectacular property of particles and antiparticles — and of matter and antimatter — is that they mutually annihilate each other on contact in a burst of energy.

The particle–antiparticle symmetry was postulated by Dirac in the late 1920's. His relativistic quantum equation suggested the existence of an anti-electron of opposite charge which was identical to the ubiquitous electron in all other respects. Four years later, in 1932, the positron was discovered in the cosmic radiation. For the proton an antiparticle had to exist as well. It was artifically produced in 1955 by colliding 5.6 GeV protons with the protons in a Cu target using the then most powerful particle accelerator.

3. The CPT theorem

There are three basic forces in our world, classified as strong, electroweak and gravitational. Strong refers to the force that binds the quarks in the nucleon. Electroweak means the unification between the electromagnetic forces and the interaction that is responsible for various beta and other slow decay processes. Gravity is familiar to everyone. The present theories of the three forces are Quantum Chromodynamics for the strong, the Standard Model for the electroweak and General Relativity for the gravitational interaction. All these theories are based on symmetry considerations.

Of particular interest are the discrete symmetries C, P, and T. Charge conjugation C changes the signs of electric charge, lepton number, and quark flavour, parity P inverts three–dimensional space and time reversal T reverses velocities and rotations. Contrary to what was initially thought, nature turned out to respect neither C nor P nor T. Also the combined symmetry CP is violated. But the simultaneous action of all three operations seems to be an exact symmetry. If particle is replaced by antiparticle (C), right by left (P) and past by future (T) all physical laws remain unchanged. This so-called CPT invariance is a fundamental theorem of quantum field theory and is not merely an aesthetic preference, as were the misplaced beliefs in individual C, P, and T invariance. It follows from the basic requirements of locality, unitarity and Lorentz invariance.

Dirac's prediction of the positron was the first example of CPT symmetry. Today the most stringent test of CPT symmetry is provided by the $K^0\overline{K^0}$ particle–antiparticle system. The K^0 is a meson of approximately half the proton mass, it is electrically neutral and has zero spin. Its mass is known to differ from that of its antiparticle, $\overline{K^0}$, by less than five parts in 10^{18} [3],

$$\frac{\mid m_{K^0} - m_{\overline{K^0}} \mid}{m_{K^0}} \leq 5 \times 10^{-18} \ . \tag{1}$$

The next best tests of CPT are provided in the leptonic sector by the comparison of the magnetic moments of the electron and the positron [4],

$$\frac{|\mu_{e^-}| - |\mu_{e^+}|}{|\mu_{e^-}|} = (+0.5 \pm 2.1) \times 10^{-12} \ , \tag{2}$$

and for baryons by the agreement between the masses of the proton and the antiproton [5],

$$m_p/m_{\overline{p}} = 1.000\ 000\ 0015 \pm 0.000\ 000\ 0011 \ . \tag{3}$$

The latter two results, although beautiful demonstrations of experimental art, appear quite crude against the $K^0\overline{K^0}$ limit. But there is no reason to conclude that testing of CPT need go no further. Given the intimate connection of the theorem with our present theories of the fundamental forces, any hint of CPT violation would have profound consequences, especially under cosmic conditions and over cosmic time scales, and could change enormously the way we have to read the history of the universe.

4. The equivalence principle

The equivalence principle is another cornerstone of our understanding of the physical world. The principle states that two objects fall with the same gravitational acceleration regardless of their mass and material composition. Here mass appears in two contexts. The inertial mass is a kinematical quantity having to do with motion, while the gravitational mass has the character of a charge: a massive object feels gravitational force in proportion to its gravitational mass just as a charged object feels an electromagnetic force in proportion to its electric charge. The equivalence principle maintains that the two types of mass, inertial and gravitational, are equivalent.

The first precision tests of the equivalence principle were performed by Eötvös at the beginning of this century. He realized that his torsion balance could discriminate between inertial mass and gravitational mass of two objects placed at opposite ends of the balance, because the net force acting on each object is made up of the gravitational attraction of the earth and the centrifugal force due to the earth's rotation. While the first component is proportional to the gravitational mass of the object, the second is proportional to its inertial mass. If two different materials were put on the balance and the ratio of inertial mass to gravitational mass for one did not equal that ratio for the other, the balance would rotate. Eötvös found equality of both masses for several substances to a precision of five parts in 10^9. More recent Eötvös–type experiments which measured the ratio of inertial mass to gravitational mass in the gravitational field of the sun have improved this limit by three orders of magnitude [6].

With this result and reminding oneself that General Relativity does not distinguish between particles and antiparticles, one might invoke CPT to argue that a piece of antimatter, when dropped, falls like a piece of ordinary matter. All that counts is the total energy which is identical for particles and antiparticles. This conclusion is valid if Einstein's General Relativity is the ultimate theory of gravitation. However, recent attemps to unify gravitation with the other two basic forces have proposed alternatives where gravity may interact with aspects of matter other than energy, such as baryon number. Within these concepts the answer of CPT is more subtle. The statement is that an antiapple would fall to an antiearth in the same way as an apple falls to the earth. Nothing is said about how an antiapple falls to an earth of ordinary matter.

A direct test is not easy in view of the minute effects of gravitation on the elementary particle scale. The electric field generated by a single unit of charge at 10 cm distance from a proton, for instance, is able to balance the gravitational force produced by all the 4×10^{51} protons and neutrons in the earth. Nevertheless, experiments in which antiatoms or antiparticles are dropped or thrown have been proposed and have even been tried in the case of positrons. The difficulty is to reduce stray electromagnetic fields to a negligible level.

A better approach might be spectroscopic measurements. An excited atom is more massive than the atom in its ground state. Therefore, when an excited atom emits a photon there will be a decrease of the atom's mass. If the atom is located in a gravitational field this change in mass is accompanied by a change in the potential energy of the atom and the emitted photon will be redshifted accordingly. Failure of antihydrogen to comply with the equivalence principle would mean that the binding energies of hydrogen and antihydrogen have different weights, resulting in different redshifts for the transition frequencies.

5. Spectroscopy of hydrogen

A good place for the comparison of hydrogen and antihydrogen is the $1S$-$2S$ transition. The reason is the exceptionally long lifetime of the $2S$-state. Electric dipole transitions to the $1S$ ground state are forbidden by angular momentum conservation and by parity, or they are extremely suppressed because of the small transition energy to the $2P$ first excited state, see Fig. 1.

The decay therefore proceeds by a 2-photon transition which, although allowed, is inherently slow. The theoretical lifetime is $1/7\,s$ [7]. From the uncertainty principle this corresponds to a quantum limit for the line width of 1.1 Hz.

The two-photon requirement in the decay is also in effect for the time-reversed process of excitation, where it opens a path to precision measurements. If the $1S$-$2S$ transition is induced by absorption of two photons, one each from two laser beams travelling in opposite directions and each of exactly half the transition frequency, the first-order Doppler effect is eliminated. Irrespective of their individual velocities all atoms are able to absorb the counter-propagating photons and the ultimate width of the observed resonance will be of the order of the quantum limit. Given sufficient counting statistics, a careful experiment might locate the line center to within a fraction of the width, raising the prospect of a $1S$-$2S$ spectroscopy in hydrogen and antihydrogen at the level of precision set by the $K^0\overline{K^0}$ system. The present value for hydrogen [8],

$$\nu(1S, F = 1 \rightarrow 2S, F = 1) = 2\ 466\ 061\ 102\ 475.12\ (84)\ \text{kHz}\ , \qquad (4)$$

is still far from this precision. Techniques for synthesizing, stabilizing, and measuring optical frequencies, however, are advancing rapidly and there is good reason to believe that the quantum limit will be beaten, in particular in a comparative measurement.

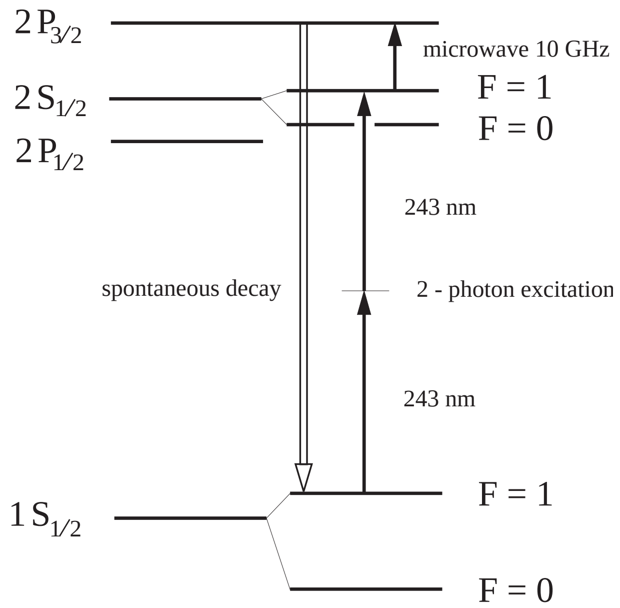

Fig. 1. Level scheme of hydrogen.

Low–lying states in atomic hydrogen. The states are labelled by the principal quantum number ($n = 1$ or 2), the orbital angular momentum of the electron (S corresponds to $l = 0$, P to $l = 1$) and by its total angular momentum ($J = 1/2$ or $3/2$). Due to the hyperfine interaction with the magnetic moment of the proton the electronic levels are split as indicated for the two S-states. The total angular momentum of the entire atom is F. The energy difference from the 1S to the $2S$-state is 10.20 eV, three quarters of the total binding energy, while the hf-splitting is 1420 MHz in the ground state, one eighth of this in the $2S$-state and weaker still in the P-states. The proposed two-photon precision spectroscopy employs a cyclic process which begins with the $1S,\ F = 1 \rightarrow 2S,\ F = 1$ transition. The excitation is monitored by a microwave quenching field which induces the transition from the metastable $2S_{1/2}$, $F = 1$ level (lifetime $\tau = 1/7s$) to the $2P_{3/2}$, $F = 2$ level ($\tau = 1.6$ ns), followed by the decay back to the $F = 1$ member of the ground state. The emitted Lyman-α photon is registered in an external detector.

A difference in the transition frequencies for hydrogen and antihydrogen — if observed eventually — could come from CPT violation but might conceivably also have its origin in a breakdown of the equivalence principle. Measurements at different gravitational potentials are able to discriminate between the two alternatives. One solution is to exploit the excentricity of the earth's orbit and let the experiment rise and fall in the gravitational potential of the sun. The solar potential at a distance of $r = 1$ AU is given by

$$\frac{G_N M_\odot}{rc^2} = 1 \times 10^{-8} , \tag{5}$$

where G_N is the gravitational constant and $M_\odot$ is the solar mass. Relevant for the measurement is the seasonal variation, which is 3 percent of the average value given by Eq. (5) and which is about 300 times larger than the potential difference from sea level to the top of Mt. Everest. A null result for the $1S$-$2S$ transition at the quantum limit thus would confirm the equivalence principle to one part in 10^6. This is about the limit to be expected for gravivector acceleration of antimatter, as set by the Eötvös–type experiments with ordinary matter [9].

6. Perspectives

The observation of relativistic antihydrogen has been confirmed at Fermilab [10], but the central question whether antimatter behaves in exactly the same way as matter remains open. Precision measurements require antihydrogen at rest. Because LEAR is no longer available, CERN is now building a new antiproton source, the antiproton decelerator, which will deliver about 10^7 antiprotons per minute with a momentum as low as 100 MeV/c. The construction schedule sees the AD ring ready to supply its first antiprotons in 1999. The experiments will use magnetic trapping techniques to create more than 1000 atoms of antihydrogen per hour and to expose them to high-resolution laser spectroscopy.

Symmetry considerations are fundamental to our perception of the laws of physics. Yet, in the world that we live in, many of these symmetries are found to be broken. The appearance of antihydrogen in the laboratory now paves the way for precision experiments that will test the symmetry of the antiworld.

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