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Testing *CPT* invariance with antiprotonic atoms

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Abstract

The structure of matter is related to symmetries on every level of study. The *CPT* symmetry is one of the most important laws of the field theory: it states the invariance of physical properties when one simultaneously changes the signs of the charge and of the spatial and time coordinates of particles. Although in general opinion *CPT* symmetry is not violated in Nature, there are theoretical attempts to develop *CPT*-violating models. The antiproton decelerator at CERN has been built to test *CPT* invariance. Its three experiments compare the properties of particles and antiparticles by studying antihydrogen, the positron–antiproton bound system and the antiprotonic helium atom.

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1. Introduction: symmetries in particle physics

Symmetries in particle physics are even more important than in chemistry or solid state physics. Just like in any theory of matter, the inner structure of the composite particles is described by symmetries, but in particle physics everything is deduced from the symmetries (or invariance properties) of the physical phenomena or from their violation: the conservation laws, the interactions and even the masses of the particles (see Halzen and Martin, 1984 for all general references).

The conservation laws are related to symmetries: the Noether theorem states that a global symmetry leads to a conserving quantity. The conservation of momentum and energy are deduced from the translational invariance of space–time: the physical laws do not depend upon where we place the zero point of our coordinate system or time measurement; and the fact that we are free to rotate the coordinate axes at any angle is the origin of angular momentum conservation.

Spin is one of the most important properties of the particles: those having half-integer spins are the fermions whereas the integer-spin particles are bosons. The different symmetries of the fermions and bosons lead to dramatic differences in their behaviour, e.g. the numbers of fermions are conserved whereas the numbers of bosons are not. The basic building blocks of the visible matter of the Universe, the quarks and leptons are fermions and all known interactions are mediated by bosons.

All fermions have *antiparticles*, antifermions which have identical properties but with opposite charges. The different abundance of particles and antiparticles in our Universe is one of the mysteries of astrophysics: apparently there is no antimatter in the Universe in significant quantities, see, e.g. Cohen et al. (1998). If there were antimatter galaxies they would radiate antiparticles and we would see zones of strong radiation at their borders with matter galaxies, but the astronomers do not see such a phenomenon anywhere.

An extremely interesting property of *antiparticles* is that they can be treated mathematically as if they were *particles*

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of the same mass and of oppositely signed charge of the same absolute value *going backward in space and time*. This is the consequence of one of the most important symmetries of Nature: *CPT* invariance (Eidelman et al. and Particle Data Group, 2004). The *CPT* reflection means the following simultaneous operations:

- charge conjugation (i.e. changing particles into antiparticles), $C\psi(r,t) = \overline{\psi}(r,t)$;
- parity change (i.e. mirror reflection), $P\psi(r,t) = \psi(-r,t)$ and
- time reversal, $T\psi(r,t) = \psi(r,-t)$.

The principle of *CPT* invariance states that this does not change the physical properties (i.e. the wave function or in the language of field theory the *field function* $\psi(r,t)$) of the system:

$$CPT\psi(r,t) = \overline{\psi}(-r,-t) \sim \psi(r,t). \tag{1}$$

This means that, e.g. the annihilation of a positron with an electron can be described as if an electron came to the point of collision, irradiated two or three photons and then went out backward in space–time.

If we build a clock looking at its design in a mirror, it should work properly except that its hands will rotate the opposite way and the lettering will be inverted. The laws governing the work of the clock are invariant under space inversion, i.e. conserve parity. As we know, the weak interaction violates parity conservation, unlike the other interactions. The weak forces violate the conservation of *CP* as well. The *CPT* invariance, however, is still assumed to be absolute. Returning to the example of the clock, a *P* reflection means switching left to right, a *C* transformation means changing the matter of the clock to antimatter and the time reversal *T* means that we play the video recording of the movement of the clock backward.

2. Testing *CPT* invariance

This principle requires, e.g. that particles and antiparticles have the same mass and have additive quantum numbers (like charge) of the same absolute value but opposite sign. Thus, a straightforward *CPT* test is measuring the mass and charge of particles and antiparticles (the best candidates being the proton and the antiproton as the heaviest stable particles).

All such laws have to be and are checked experimentally. The *CPT* invariance is so deeply embedded in field theory that many theorists claim it is impossible to test within the framework of present-day physics. Indeed, in order to develop *CPT*-violating models one has to reject such fundamental axioms as Lorentz invariance or the locality of interactions (i.e. causality) or unitarity (Kostelecký, 2004; Mavromatos, 2005; Klinkhamer and Rupp, 2004).

As far as we know, the standard model is valid up to the Planck scale, $\sim 10^{19}$ GeV. Above this energy scale we expect to have new physical laws which may allow for Lorentz and *CPT* violation as well (Kostelecký, 2004). Quantum gravity (Mavromatos, 2005; Klinkhamer and Rupp, 2004) could cause fluctuations leading to Lorentz violation or loss of information in black holes which would mean unitarity violation. Also, a quantitative expression of Lorentz and *CPT* invariance needs a Lorentz and *CPT*-violating theory (Kostelecký, 2004). On the other hand, testing *CPT* invariance at low energy should be able to limit possible high-energy violation. This makes experimental *CPT* tests physically valuable in spite of the fact that most of us do not expect its violation.

The *CPT* invariance is so far fully supported by the available experimental evidence and it is absolutely fundamental in field theory. Nevertheless, there are many experiments trying to test it. The simplest way is to compare the mass or charge of particles and antiparticles. The most precise such measurement is that of the relative mass difference of the neutral K meson and its antiparticle: it is less than 10^{-18} (Eidelman et al. and Particle Data Group, 2004).

The CERN has constructed its *antiproton decelerator* (*AD*) facility (The Antiproton Decelerator at CERN) in 1999 in order to test the *CPT* invariance by comparing the properties of proton and antiproton and those of hydrogen and antihydrogen (Fig. 1). The AD was constructed mainly using outside funds and started to operate at the end of 1999. By the end of 2000 it was brought to specifications. The 25 GeV/c protons from the proton synchrotron are shot in an iridium target where they produce particle–antiparticle pairs. Antiprotons are collected at 3.5 GeV/c momentum and slowed down in the AD ring in three steps to 100 MeV/c using stochastic and electron cooling.

The aim of the present work is to briefly summarize some of the results of the AD experiments, ASACUSA (ASACUSA Collaboration), ATHENA (ATHENA Collaboration) and ATRAP (ATRAP Collaboration).

3. Antihydrogen

Antihydrogen, the bound system of an antiproton and a positron, stands in the centre of interest of the low-energy antiproton community. The reason is that antihydrogen spectroscopy offers to test several fundamental principles of physics, the most important ones being *CPT* symmetry and the weak equivalence principle of gravity (Charlton et al., 1994; Holzscheiter et al., 2004). According to *CPT* invariance an antiproton should accelerate the same way in the gravitational field of an anti-Earth as protons in that of Earth. The weak equivalence principle states the same for an antiproton in the field of Earth. Unfortunately, it is very hard to test experimentally as the gravitational force on an antiproton at the surface of Earth is about the same as the electric force of a point charge from a distance of 10 cm. Such a test is proposed using the effect of the different gravitational force of the Sun in winter and summer on the atomic transitions of antihydrogen (Charlton et al., 1994).