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Nuclear Instruments and Methods in Physics Research B 233 (2005) 95–102

NIM B Beam Interactions with Materials & Atoms

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Effects of collisions on antiprotonic atoms ☆

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Available online 25 April 2005

Abstract

A brief review is given of three experiments at the Antiproton Decelerator at CERN to test *CPT* invariance which states that particles and antiparticles have identical properties, in particular the same mass and opposite charge. Two experiments, ATHENA and ATRAP aim to study atomic transitions at high precision on antihydrogen, the antiproton–positron atom, as compared to ordinary hydrogen. The third experiment, ASACUSA, performs spectroscopy of antiprotonic helium to measure the charge and mass of the antiproton, at present with the precision of 10 ppb.

Collisions play an important role in these studies. The capture of the antiproton in bound state happens in collisions. Collisions (especially those with foreign atoms) can destroy the freshly formed system, and collisions with the medium or residual gas changes its lifetime and energy levels.

PACS: 36.10.Gv; 11.30.Er; 14.20.Dh; 32.30.Jc

Keywords: Exotic atom; Cascade decay; Ion trap; Laser spectroscopy; Antiprotonic helium; Antihydrogen; *CPT* invariance

1. Motivation: *CPT* invariance

CPT invariance is one of the most basic symmetries of physics. It states that the operations of *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*, $T\psi(r,t) = \psi(r,-t)$ when done simultaneously do not change the physical properties of the system:

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

As a consequence of this symmetry, when calculating cross-sections one treats an antiproton as a proton going backward in space-time.

This principle requires, e.g. that particles and antiparticles have the same mass and have additive quantum numbers (like charge) of the same

☆ Invited talk presented at FIAC'04, 8th Workshop on Fast Ion-Atom Collisions, Debrecen, 1–3 September 2004.

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0168-583X/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.nimb.2005.03.091

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. However, *CPT* invariance seems to be so deeply embedded in field theory that one has to give up causality and locality in order to develop a theory without it. Thus as long as we do not see a difference pointing to *CPT* violation we can say that *CPT* works; in the opposite case one expects serious debates concerning the real cause of the deviation.

The Antiproton Decelerator [1] of CERN was built in 1999 for testing the *CPT* symmetry.

2. The Antiproton Decelerator (AD) at CERN

When CERN's Low Energy Antiproton Ring (LEAR) was closed in 1996 its users applied for a dedicated low-energy machine to be built. 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. 27 GeV 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 AD hall houses four experiments, three of them study *CPT*: ASACUSA[1] [2], ATHENA [3] and ATRAP [4]. ATHENA and ATRAP aim at measuring the 2S–1S two-photon transition in antihydrogen, the bound state of an antiproton and a positron [5] in comparison with that in ordinary hydrogen whereas ASACUSA studies antiprotonic atoms and works on developing a source of very slow antiprotons.

[1] Asakusa is one of the oldest districts of Tokyo; the name was proposed by our non-Japanese collaborators to honour the dominant Japanese contribution to the experiment.

3. Antiprotonic helium atoms

An exotic atom is formed when a fast negative particle – muon, pion, kaon or antiproton – penetrates matter: it first slows down in atomic collisions (mostly via ionization), then gets captured in an atomic orbit *replacing* the last knocked-out electron. The capture cross-section is related to the overlap between the wave functions of the particle and the atomic electron so the heavy particle will initially populate atomic states with radii close to that of the electrons. Thus an antiproton captured, e.g. in a helium atom will initially populate the $\bar{p}He^+$ states with principal quantum numbers $n_0 = \sqrt{M/m} \approx 38$ where $M \approx 0.8m_p$ and $m \approx m_e$ are the reduced masses of the $\bar{p}He^{2+}$ and e^-He^{2+} systems. A high n, naturally, involves orbital quantum numbers in the region $0 \leqslant \ell \leqslant n-1$; and although experiments found deviations of the initial populations from a purely statistical $2\ell + 1$ distribution, the states with higher ℓ will be populated with higher probability.

The freshly formed, highly excited exotic atom has two basic ways to step down. Between high-n states, where the energy spacing is low, the Auger mechanism dominates whereas lower lying levels will preferably decay via radiation. Approaching the ground state a strongly interacting hadron like the antiproton gets absorbed by the nucleus from higher nS levels and it hardly reaches ground state in heavier atoms. Both in condensed media and in gases at higher pressures (about standard conditions) slowing down, atomic capture, de-excitation and nuclear absorption proceeds quite fast: theoretical calculations and experimental measurements agree upon total lifetimes below or around 1 ps (10^{-12} s).

The only exception is helium: while 97% of the antiprotons stopped in a dense helium target annihilate with the usual short lifetimes, 3% live as long as several microseconds, sufficiently long to use laser spectroscopy. They form a $\bar{p}He^+$ three-body system where the antiproton orbit is protected against collisions by the electron, and the antiprotonic states of the same n but different ℓ lose the energy degeneracy and so cannot undergo Stark transitions. The model and its experimental proof are described in reviews [6–8].