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Review

Physics at CERN's Antiproton Decelerator

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ABSTRACT

The Antiproton Decelerator (AD) facility of CERN began operation in 1999 to serve experiments for studies of *CPT* invariance by precision laser and microwave spectroscopy of antihydrogen ($\overline{\mathrm{H}}$) and antiprotonic helium ($\overline{p}\mathrm{He}^+$) atoms. The first 12 years of AD operation saw cold $\overline{\mathrm{H}}$ synthesized by overlapping clouds of positrons (e^+) and antiprotons ($\overline{p}$) confined in magnetic Penning traps. Cold $\overline{\mathrm{H}}$ was also produced in collisions between Rydberg positronium (Ps) atoms and $\overline{p}$. Ground-state $\overline{\mathrm{H}}$ was later trapped for up to $\sim$1000 s in a magnetic bottle trap, and microwave transitions excited between its hyperfine levels. In the $\overline{p}\mathrm{He}^+$ atom, deep ultraviolet transitions were measured to a fractional precision of $(2.3–5) \times 10^{-9}$ by sub-Doppler two-photon laser spectroscopy. From this the antiproton-to-electron mass ratio was determined as $M_{\overline{p}}/m_e = 1836.1526736(23)$, which agrees with the p value known to a similar precision. Microwave spectroscopy of $\overline{p}\mathrm{He}^+$ yielded a measurement of the $\overline{p}$ magnetic moment with a precision of 0.3%. More recently, the magnetic moment of a single $\overline{p}$ confined in a Penning trap was measured with a higher precision, as $\mu_{\overline{p}} = -2.792845(12)\mu_{\mathrm{nucl}}$ in nuclear magnetons. Other results reviewed here include the first measurements of the energy loss ($-dE/dx$) of 1–100 keV $\overline{p}$ traversing conductor and insulator targets; the cross sections of low-energy ($<$10 keV) $\overline{p}$ ionizing atomic and molecular gas targets; and the cross sections of 5 MeV $\overline{p}$ annihilating on various target foils via nuclear collisions. The biological effectiveness of $\overline{p}$ beams destroying cancer cells was measured as a possible method for radiological therapy. New experiments under preparation attempt to measure the gravitational acceleration of $\overline{\mathrm{H}}$ or synthesize $\overline{\mathrm{H}}^+$. Several other future experiments will also be briefly described.

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1. Introduction

The Antiproton Decelerator (AD) facility of CERN [1,2] began operation in 1999 to carry out high-precision laser spectroscopy of antihydrogen ($\overline{\text{H}}$) and antiprotonic helium ($\overline{p}\text{He}^+$) atoms. It was envisaged that by comparing the characteristic transition frequencies of these atoms with the corresponding ones for hydrogen (H) in the $\overline{\text{H}}$ case, or quantum electrodynamics (QED) calculations in the $\overline{p}\text{He}^+$ case at the highest possible precision, the consistency of *CPT* invariance could be tested. This invariance is deeply engrained within the Standard Model of particle physics, and implies that particles and their antiparticle counterparts should have exactly the same mass, and charges and magnetic moments of the same values but opposite signs. Atoms should resonate at exactly the same frequency as "anti-atoms" made of antiparticles.

Precision laser and microwave spectroscopy of atoms and ions of ordinary matter have been carried out for more than 50 years, and in recent years have achieved such a high level of sophistication that transition frequencies have routinely been measured with an experimental precision of better than 10^{-15}. This exceeds even the precision by which the international definition of the second can be currently determined. Some experiments are sensitive to minute shifts in the frequencies due to the effects of General Relativity. Progress on the anti-atom side is much more difficult due to the simple fact that cold samples are so difficult to synthesize in large quantities. The constituent antiprotons ($\overline{p}$) and positrons (e^+) can only be produced in very small quantities in laboratory nuclear reactions at MeV or GeV energy scales. These particles cannot be