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Progress with cold antihydrogen

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Abstract

The creation of cold antihydrogen by the ATHENA and ATRAP collaborations, working at CERN's unique Antiproton Decelerator (AD) facility, has ushered in a new era in atomic physics. This contribution will briefly review recent results from the ATHENA experiment. These include discussions of antiproton slowing down in a cold positron gas during antihydrogen formation, information derived on the dependence of the antihydrogen formation rate upon the temperature of the stored positron plasma and, finally, upon the spatial distribution of the emitted anti-atoms. We will discuss the implications of these studies for the major outstanding goal of trapping samples of antihydrogen for precise spectroscopic comparisons with hydrogen. The physics motivations for undertaking these challenging experiments will be briefly recalled.

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1. Introduction and motivations

The creation of low energy antihydrogen [1,2] is a landmark in atomic physics research. This achievement has

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spawned an explosion of theoretical activity in cognate areas of atomic and plasma physics, fuelled by further experimental advances by the ATHENA [3–7] and ATRAP [8–10] collaborations. Reviews of some of this work have been given elsewhere recently [11,12].

The main physics motivations for antihydrogen production lie in the promise for tests of CPT symmetry and antimatter gravity. CPT is a theorem in local quantum field theory in which the three quantum mechanical transformations of C (charge conjugation), P (parity) and T (time reversal) are combined. There are no known violations of this symmetry (see e.g. [13] for a summary of limits), but expectations are that modern theories of particle physics, that treat particles as extended objects rather than points, may contain CPT violation (see e.g. [11] and references therein). In this respect, precise hydrogen–antihydrogen comparisons may provide an important testing ground for new physics.

Gravity remains the "odd one out" in terms of Grand Unification. Indeed, as is well known, there is currently no acceptable quantum theory of gravity. In addition, we have no information on the gravitational interaction of antimatter. For instance, all we can glean from CPT is that antihydrogen will fall as fast towards a hypothetical anti-Earth as hydrogen does towards Earth. Given the current state of affairs either quantum mechanics or general relativity (or both of them) are incomplete. At the very least this makes gravity on antimatter an interesting phenomenon to study.

2. Experimental details

The ATHENA antihydrogen apparatus has been described in detail elsewhere [14]. The apparatus has three essential parts: a positron beam, accumulator and transfer section; an antiproton catching trap and associated Penning traps to promote antihydrogen formation; an antihydrogen annihilation detector. We briefly describe these here.

Low energy positron beams (see e.g. [15,16] and this volume) are now a standard feature in many physics laboratories. ATHENA used a solid neon moderator-based positron beam, derived from a ^{22}Na source, coupled to a buffer gas-cooled Penning–Malmberg trap [17–20]. In excess of 100 million positrons were accumulated in this apparatus, in about 3 min, and then transferred efficiently [21] to the antiproton apparatus. Further manipulation of the positron plasma in the 3 T magnetic field, cryogenic environment (15 K), of the antiproton traps could be undertaken using the rotating electric field technique [21–23]. Typically around 80 million positrons at a density of about 2×10^8 cm^{-3} were used for antihydrogen formation. The temperature of the positron cloud could be raised by applying a radio frequency signal to one of the trap electrodes surrounding the plasma. The temperature change was monitored non-destructively using a specially developed technique based upon the excitation and detection of plasma mode frequencies [24,25].

Antiprotons were captured and cooled using the well-documented procedure developed at CERN by Gabrielse and co-workers [26,27] and applied to form large antiproton clouds by the PS200T collaboration [28,29]. A 100 ns wide burst of about 2×10^7 antiprotons was ejected from the AD about every 100 s or so at a kinetic energy just above 5 MeV. About 1 in a 1000 of these could be dynamically captured in a 5 kV deep catching trap following energy degradation on passing through a carefully optimized thin foil. Once held in the 3 T Penning trap, the antiprotons were further cooled by interaction with a pre-loaded cloud of about 10^8–10^9 electrons, which self-cool in the strong field to the ambient temperature of 15 K. After about 10 s the antiprotons, which Coulomb couple efficiently to the electron cloud as they pass to-and-fro through it, reach thermal equilibrium with the electrons and occupy a small harmonic trap. The electrons can easily be removed by the application of short voltage pulses to leave about 10^4 antiprotons for release into the positron plasma.

Both the ATRAP and ATHENA collaborations have applied the nested Penning trap approach [30] to promote antihydrogen formation, and the system used by ATHENA is illustrated in Fig. 1. Here the axial electric potential, provided by the voltages applied to the

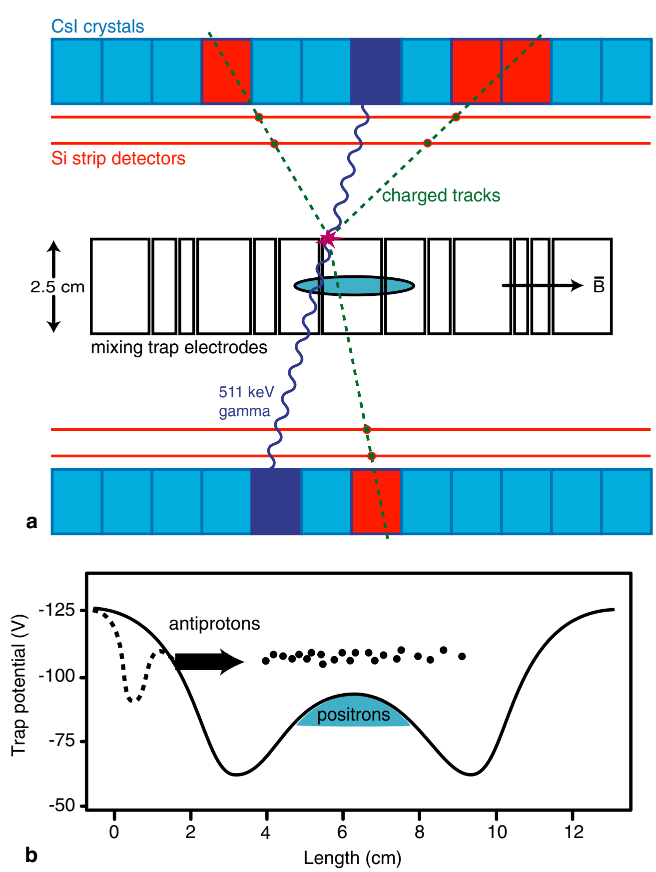

Fig. 1. (a) Schematic illustration of the ATHENA nested well apparatus with pion and γ-ray detectors included. (b) On-axis nested well potential showing the antiproton well (dashed line) before mixing.