EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–EP/2001–084
16 November 2001

Producing Slow Antihydrogen for a Test of CPT Symmetry with ATHENA

M.C. Fujiwara[8),]M. Amoretti[4)], C. Amsler[10)], G. Bendiscioli[6)], G. Bonomi[2)], A. Bouchta[3)], P. Bowe[1)], C. Carraro[4)], M. Charlton[9)], M. Collier[9)], M. Doser[3)], V. Filippini[6)], K. Fine[3)], A. Fontana[6)], R. Funakoshi[8)], P. Genova[6)], D. Grögler[10)], J.S. Hangst[1)], R.S. Hayano[8)], H. Higaki[8)], M.H. Holzscheiter[5)], W. Joffrain[4)], L. Jorgensen[9)], V. Lagomarsino[4)], R. Landua[3)], C. Lenz Cesar[7)], D. Lindelöf[10)], E. Lodi-Rizzini[2)], M. Macri[4)], N. Madsen[10)], G. Manuzio[4)], M. Marchesotti[3)], P. Montagna[6)], H. Pruys[10)], C. Regenfus[10)], P. Riedler[3)], A. Rotondi[6)], G. Rouleau[3)], P. Salvini[6)], G. Testera[4)], D.P. van der Werf[9)], A. Variola[4)], L. Venturelli[2)], T. Watson[9)], T. Yamazaki[8)], and Y. Yamazaki[8)]

(ATHENA collaboration)

ABSTRACT

The ATHENA experiment at the Antiproton Decelerator facility at CERN aims at testing CPT symmetry with antihydrogen. An overview of the experiment, together with preliminary results of development towards the production of slow antihydrogen are reported.

(To be published in Hyperfine Interactions)

[1)] University of Aarhus, Denmark,
[2)] Brescia University & INFN, Italy,
[3)] CERN, Switzerland,
[4)] Genoa University & INFN,
[5)] Los Alamos Nat. Lab., USA,
[6)] Pavia University & INFN, Italy
[7)] Fed. Univ. Rio de Janeiro (UFRJ), Brasil,
[8)] University of Tokyo, Japan,
[9)] University of Wales Swansea, UK,
[10)] University of Zurich, Switzerland

1 Introduction

Testing symmetries is one of the important subjects in physics. While P (parity) and CP (charge-parity) are known to be violated, CPT (charge-parity-time reversal) is believed to be conserved by virtue of the CPT theorem [1]. The assumptions of the CPT theorem do not, however, apply to some extensions of the Standard Model including, notably, string theories [2]. The possibility of large extra dimensions [3] may even lead to CPT violation at the energy scale much lower than the Planck scale. Several accurate tests of CPT invariance have been performed on leptons and hadrons, and in exotic atoms [4], yet given its fundamental importance, CPT should be tested in all particle sectors.

The first production of antihydrogen, a bound system of antiproton ($\overline{p}$) and positron (e^+), was reported at CERN [5], and later at Fermilab [6]. These anti-atoms, created at high velocity, annihilated almost immediately after their production, leaving little time to study their properties. It is the goal of ATHENA (AnTiHydrogEN Apparatus) to produce a large quantity of slow antihydrogen to study its properties and, via comparison with its well-studied matter counterpart, to make precision tests of the CPT and other symmetries of nature [7]. Phase 1 of ATHENA focuses on production and identification of slow antihydrogen. In this paper, we describe the overview of the experiment together with recent progress towards making slow antihydrogen.

2 ATHENA Overview

ATHENA is one of the three experiments at CERN's newly constructed Antiproton Decelerator (AD) facility. ASACUSA [8] and ATRAP [9] are other experiments studying antiprotonic atom spectroscopy/collision, and antihydrogen, respectively. The AD, commissioned for physics in July, 2000, provides a pulse of a few $\times 10^7$ $\overline{p}$ at 100 MeV/c (5.3 MeV in kinetic energy) roughly every two minutes, with its performance steadily improving.

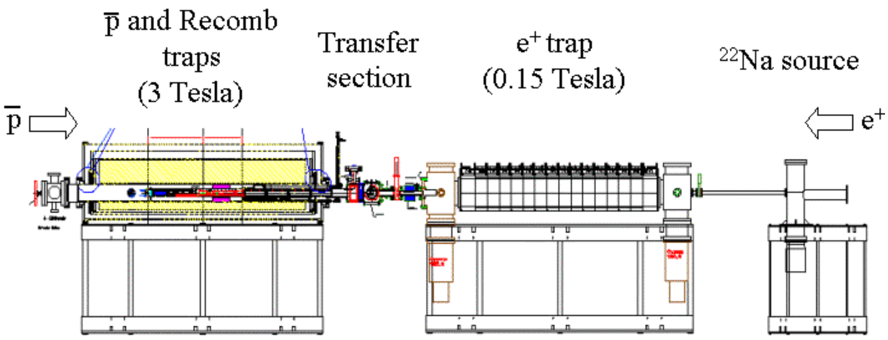

Figure 1: The ATHENA Apparatus

The ATHENA experiment consists of four major components: a catching trap, a recombination trap, a positron accumulator, and the detection system (Fig. 1). Antiprotons, first trapped in the catching trap and cooled by electrons, are subsequently moved to the recombination trap. Positrons are separately trapped in the positron accumulator, and then transferred to the recombination trap, where they are merged with antiprotons. Antihydrogen, formed via recombination of two ingredients, escapes the trap confinement and collides with the wall, thereby annihilating. Antihydrogen annihilation will be detected by the ATHENA vertex detector, consisting of Si micro-strips and segmented CsI crystals. In addition, several other detectors are used to study the trapping and cooling of antiprotons, which include a segmented Si beam counter, a Faraday cup, a CCD camera, and external scintillators coupled either to photo-multipliers or HPDs (hybrid photodiodes) [10].

3 Antiproton Catching and Cooling

Antiprotons are trapped in an open end-cap Penning trap [11] in which the radial motion is confined by a 3 Tesla magnetic field in a superconducting solenoid, and the axial motion, by an electrostatic potential ranging from 5 to 10 kV. A pulsed beam of 5.3 MeV antiprotons from the AD passes through a segmented Si beam detector, and slowed by a stainless steel vacuum window and an Al degrader to less than 10 keV upon injection into the catching trap. The entrance side of the trap potential is opened for a few hundred ns when the beam arrives, in order to allow the antiprotons to enter the trap.

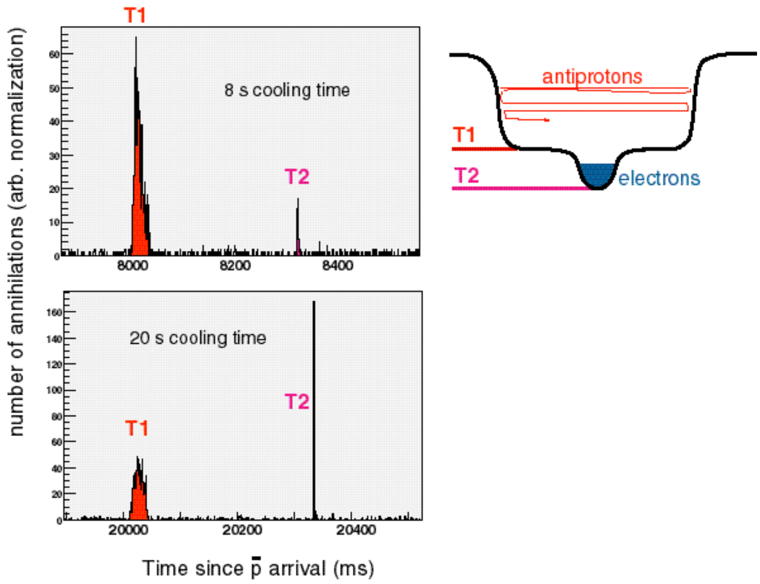

Figure 2: Electron cooling of antiprotons.

A few $\times 10^8$ electrons, preloaded in the central part of the trap, interact with trapped antiprotons and cool them to ∼eV energy or below. Figure 2 illustrates the demonstration of electron cooling in the ATHENA catching trap. The outer potential wall (5 kV) and the inner potential wall (40 V) were opened at time T1 and T2, respectively, dumping the antiprotons onto a foil. The annihilations of the released antiprotons at each time, detected by the scintillators, indicate the number of uncooled ("hot"), and cooled ("cold") antiprotons. A systematic measurement of the cooling process is shown in Fig. 3. The efficiency of electron cooling depends rather sensitively on the electron loading conditions, an effect which requires further investigation. The lifetime of trapped antiprotons is longer than several hours: it is possible to store them in our trap over night, if necessary.

4 Detecting Antihydrogen

The formation of antihydrogen will take place in the recombination trap, to which cooled antiprotons as well as positrons, the latter trapped with the nitrogen buffer gas method [12], are transferred. Several recombination schemes are discussed in Ref. [7].

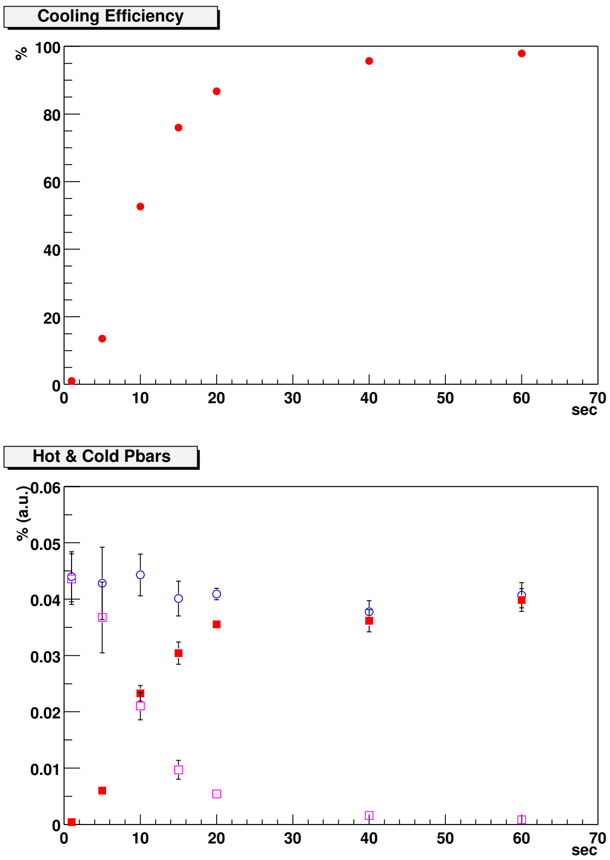

Figure 3: Top: The ratio of antiprotons cold/(cold+hot) as a function of cooling time. Bottom: The numbers of cold (plotted with filled square), hot (open square), and cold+hot (open circle) antiprotons, normalized to the beam intensity.

The ATHENA vertex detector surrounds the recombination region. The production of antihydrogen will be identified by the simultaneous detection (within $\sim 2\ \mu s$) of charged pions from the $\overline{p}$ annihilation, and back-to-back 511 keV γ rays from the e^+ annihilation, both originating from the same vertex (Fig. 4). Two layers of double sided Si micro-strips, and 16×12 pure CsI crystals coupled to photodiodes, a total of 8192 channels of signals, are read out, and the events will be reconstructed off-line.

Figure 4 (right) is an example of simulated antihydrogen events, shownig the detector front view of four charged pion tracks and back-to-back γs. A dominant source of 511 keV background is expected to come from the annihilation of e^+ produced in π^0 decay and subsequent electromagnetic showers in the surrounding material. These γs, however, would have angular correlations that are generally random, hence can be discriminated against by plotting the opening angles of two γs with respect to the reconstructed charged vertex. Hence, a high degree of CsI segmentation is important in overcoming this background.

Preliminary simulations have been performed, assuming a background of simultaneous $\bar{p}$ and e^+ annihilations with the same frequency as antihydrogen, but occurring randomly in different points on the trap walls. The results indicate that a signal-to-background ratio greater than 70 may be obtained for the opening angle θ of $-1 \leq \cos\theta \leq -0.9$ (see Fig. 5 [13]).

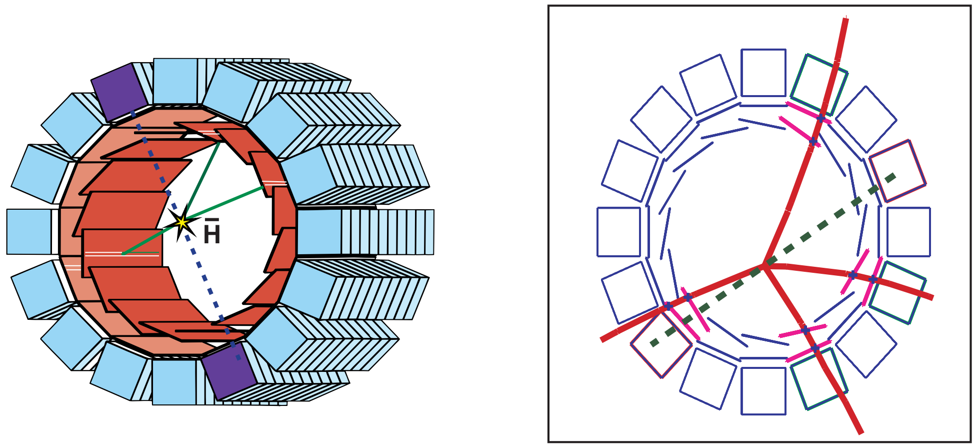

Figure 4: Left: Schematic view of the ATHENA vertex detector. Right: A GEANT simulated antihydrogen event showing 511 keV γs (dashed line) and charged pions (solid line).

5 Summary and Outlook

Since the physics start in July 2000, the ATHENA experiment has succeeded in trapping and cooling more than 10^4 antiprotons per AD pulse, accumulating more than 10^7 positrons in one minute, and transferring them to the recombination trap (although not yet at the same time). In year 2001, we will make our first attempt to merge the two species to produce slow atoms of antihydrogen.

References

[1] G. Luders, Ann. Phys. **2**, 1 (1957).

[2] see, e.g. *CPT and Lorentz Symmetry* ed. V. A. Kostelecký, World Scientific, Singapore, 1999.

[3] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B **429**, 263 (1998).

[4] Review of Particle Physics, D. E. Groom *et al.*, Eur. Phys. Jour.C **15**, 1 (2000).

[5] G. Bauer *et al.,* Phys. Lett. B **368**, 251 (1996).

[6] G. Blanford *et al.,* Phys. Rev. Lett. **80**, 3037 (1998).

[7] M. H. Holzscheiter and M. Charlton, Rep. Prog. Phys. **62**, 1 (1999).

[8] CERN Proposal SPSC 97-19/P307; see also Y. Yamazaki, and E. Widmann, this volume.

[9] CERN Proposal SPSC 97-8/P306.

[10] M.C. Fujiwara, D. Grassi and M. Marchesotii, to be published in Nucl. Instrum. and Meth.

[11] G. Gabrielse *et al.,* Phys. Rev. Lett. **57**, 2504 (1986); **63**, 1360 (1989);
M. H. Holzscheiter *et al.,* Phys. Lett. A **2214**, 279 (1996).

[12] T. J. Murphy and C. M. Surko, Phys. Rev. A **46** 5696 (1992).

[13] A. Rotondi *et al.*, ATHENA technical report (unpublished).

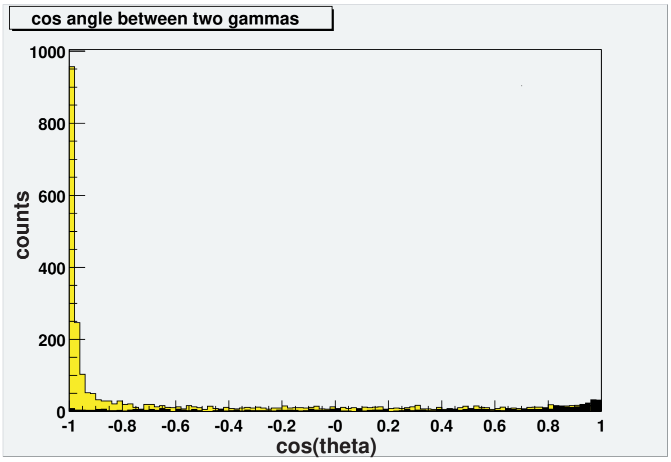

Figure 5: GEANT simulation of the opening angle θ between two 511 keV γs with respect to the reconstructed charged vertex, for the antihydrogen events (light histogram) and the random background (dark histogram).