Results from ATHENA

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Abstract. The ATHENA experiment at CERN produced for the first time in 2002 cold antihydrogen atoms by mixing of antiprotons and a positron plasma. The more relevant results obtained in the last three years are presented and discussed in the light of the antihydrogen formation processes.

Keywords: Antihydrogen; Recombination; Penning trap; Positron plasma; Antiprotons
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INTRODUCTION

Antihydrogen physics started in 1996 when the PS210 experiment at CERN reported the production of the first 9 atoms of antihydrogen [1]. Soon after the E862 experiment at Fermilab confirmed, with another 100 antiatoms, that the creation of antihydrogen was possible [2]. Both of these experiments generated in-flight antiatoms with a very low efficiency and at high energies, rendering practically impossible any further atomic physics study. In 2002 the next generation experiments at CERN, first ATHENA [3] and then ATRAP [4], reported the production of cold antihydrogen by mixing antiprotons ($\bar{p}$ s) and positrons at low temperature in a nested Penning trap [5].

In the future the creation of a sample of trapped and laser cooled antihydrogen ($\overline{H}$) atoms to temperatures in the mK range will be a huge step toward a class of entirely new

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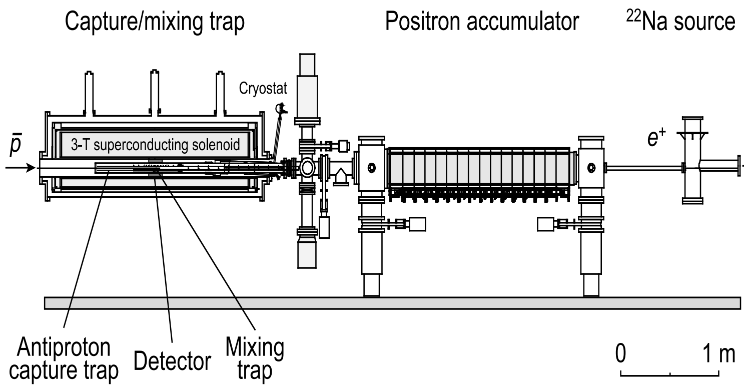

FIGURE 1. Overview of the ATHENA apparatus. Shown on the left is the superconducting 3-T solenoid magnet which houses the capture trap, the mixing trap, and the antihydrogen annihilation detector. On the right, the radioactive sodium source for the positron production and the 0.14-T positron accumulation Penning trap.

and crucial experiments on antihydrogen spectroscopy and antimatter gravity tests.

The ATHENA apparatus [6] (see Fig. 1) uses antiprotons delivered by CERN's Antiproton Decelerator (AD) and positrons emitted from a ^{22}Na radioactive source (1.4×10^9 Bq). Both the $\bar{\mathrm{p}}$ s and the positrons are trapped, cooled and accumulated in separated traps prior to moving and mixing in a common trap (called the *mixing* trap) in the central region. The positron accumulation trap is located inside a room temperature vacuum chamber in a 0.14 T magnetic field. The antiproton capture trap and the mixing trap are located in the 3-T field of a superconducting magnet whose bore is kept at 130 K under normal operation. A liquid-helium cryostat reduces the temperature of the trap region to about 15 K. Ultra-high vacuum conditions are also provided. The 3 Tesla solenoidal magnetic field which provides the radial confinement also allows positrons to cool efficiently (with a time constant $\tau \simeq 0.5$ sec) to the trap temperature by the emission of synchrotron radiation.

When formed inside the mixing trap, neutral $\overline{\mathrm{H}}$ atoms that survive collisions and field ionization, escape the confinement region and annihilate on the trap electrodes producing a signal in the surrounding vertex detector [7] that triggers the detector readout with an efficiency of 85 ± 10 %. The decay products of the annihilations (charged πs from the $\bar{\mathrm{p}}$, γs from the e^+) are then reconstructed and three-dimensional imaging of antiproton and positron annihilations in the Penning trap is possible [8, 9].

ANTIHYDROGEN PRODUCTION AND BACKGROUND IDENTIFICATION

ATHENA studied $\overline{\mathrm{H}}$ formation in different mixing cycles, by varying the cycle duration and the positron plasma temperature.

In the “standard mixing cycle" the mixing trap is configured as a nested Penning trap

TABLE 1. $\overline{\mathrm{H}}$ production from the cold mixing cycles. The uncertainty on the number of produced $\overline{\mathrm{H}}$ and injected $\overline{\mathrm{p}}$ is $\pm 5\%$.

	Long Cold Mix	Short Cold Mix
# of cycles	341	416
cycle duration (s)	180	70
total mixing time (s)	61380	29100
injected $\overline{\mathrm{p}}$	2924000	5065000
produced $\overline{\mathrm{H}}$	494000	759000
$\overline{\mathrm{H}}$ production per cycle	1450 ± 80	1820 ± 90
$\overline{\mathrm{H}}$ production rate (Hz)	8.0 ± 0.4	26.0 ± 1.3
$\overline{\mathrm{p}}$ background (%)	35 ± 5	20 ± 3
$\overline{\mathrm{H}}$ production per injected (%) $\overline{\mathrm{p}}$	17 ± 2	15 ± 2

[5], a configuration that allows simultaneous trapping of oppositely charged particles. The central part of the trap is then filled with about 3-7 $\times$ 10^7 e^+s. Once the positrons have self-cooled by synchrotron radiation, about 10^4 $\overline{\mathrm{p}}$ s are injected and the two particle species interact for about 1-3 minutes. At the start of each mixing cycle the antiprotons are cooled by their passage through the positron plasma, and after few tens of ms antihydrogen formation begins [10, 11]. At the end of the mixing cycle the nested trap is emptied and both the number of positrons and antiprotons are counted before the process is restarted.

In the cold mixing cycle, when the positron temperature was that of the trap at 15 K, most of the annihilations took place on the trap electrodes because $\overline{\mathrm{H}}$, being neutral, flew out isotropically and annihilated on the trap walls; the background was due to a small fraction of antiprotons annihilating in the trap center on rest gas atoms or ions.

In the hot mixing cycle, when the positron plasma is heated up to 3000 K, by exciting its axial dipole resonance (around 20 MHz), only the background events are observed [11, 12, 13]. The detector allows the different events to be fully identified and disentangled. The method is based mainly on the fit of some expected signal plus background distributions to the observations [8]. Two of these distributions, the vertex radial density and the opening angle cosine, are shown in fig 2.

The radial density represents the antiproton annihilation vertex position as reconstructed by the hits of the charged mesons in the two silicon strip layers of the detector. The profile of the hot mixing distribution (shaded histogram) shows clearly the presence of annihilations in the volume occupied by the positron potential well, where presumably positive ions of the residual gas are trapped. The presence of this background is at present under study, since there are indications that antiprotonic atoms may be created in this manner.

The cosine of the opening angle distribution represents $\theta_{\gamma\gamma}$ of the two 511-keV γ rays recorded in time coincidence with the charged-particle hits, as seen from the charged-particle vertex. The clear excess at $\cos(\theta_{\gamma\gamma}) = -1$ (corresponding to a back-to-back emission of the two γs typical of the $e^+ - e^-$ annihilation) is a proof of the presence of antihydrogen [3, 8]. It is also important to note that the flat part of the distribution contains antihydrogen signal, in the cases in which the detector or the reconstruction software were inefficient in the detection of both 511-keV γs. This inefficiency is mainly

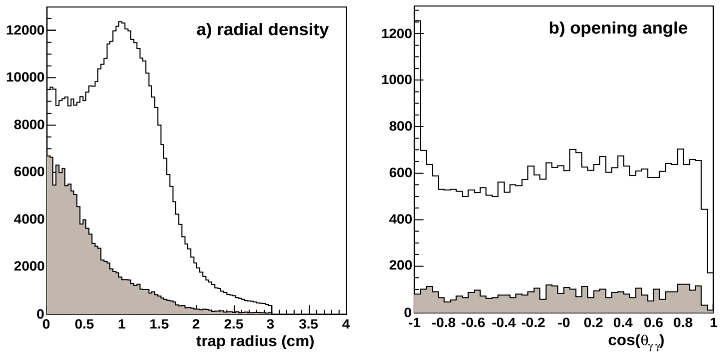

FIGURE 2. (a) Charged-meson vertex distribution as a function of the trap radius; (b) Opening-angle distribution of the photons recorded in coincidence with the charged-particle hits, as seen from the meson vertex. The shaded histograms refer to the background measured during the hot mixing cycles. All the histograms are normalized to the number of antiprotons used in the cold mixing cycles.

due to the presence of many low energy γs coming from the e.m. showers generated from the π^0 decay high energy γs in the magnet coils. As the MC calculations have shown [8], the possibility to still extract a clear $\cos(\theta_{\gamma\gamma}) = -1$ peak in these highly unfavorable conditions comes from the high granularity of our crystal detector.

The $\overline{\mathrm{H}}$ production for two different mixing times is shown in Table 1; these data represent the best results obtained so far for $\overline{\mathrm{H}}$ production with a nested Penning trap.

We see that the shorter cycle data decreases the $\overline{\mathrm{p}}$ background from 35% to about 20%, with only a small decrease of the yield per injected antiproton (from 17% to $\simeq$ 15%).

RESULTS

After having found the optimum conditions to proceed routinely, ATHENA studied systematically the dependence of the antihydrogen production on the temperature and on the density and shape of the positron plasma.

In [10] the time evolution of the cooling process was studied in detail. The existence of promptly produced antiatoms resulting from antiprotons that radially overlap with the positron cloud and quickly recombine ($t \simeq 10$ ms) has been shown, together with the presence of antiprotons that cool more slowly and represent a source of $\overline{\mathrm{H}}$ for tens of seconds.

In [11] we measured, for the first time, $\overline{\mathrm{H}}$ production as a function of the positron plasma temperature from 15 K up to more than 3000 K. A clear decrease of the antihydrogen production with temperature has been seen, but a simple power law scaling does not fit the data. The fall-off in antihydrogen production is slow enough that when the positron plasma is at room temperature the rate is still 1/3 of that observed in standard cold mixing conditions (15 K).

To discuss these results we recall that two main processes are involved in the $\overline{\mathrm{H}}$

formation: *radiative* ($e^+ + \overline{\mathrm{p}} \rightarrow \overline{\mathrm{H}} + \gamma$) and *three-body combination* ($e^+ + e^+ + \overline{\mathrm{p}} \rightarrow \overline{\mathrm{H}} + e^+$) [14]. The first process is the inverse of the photoelectric effect, the second one is the inverse of the ionization by collision and strongly depends on the plasma conditions and on the trap dynamics.

The radiative recombination in its simplest form, assuming 10^4 antiprotons interacting with a plasma of 1.7×10^8 positrons/cm^3, with complete overlap between the two particle clouds, gives a peak trigger rate of 40 Hz [11]. This is in contrast with ATHENA, which observes a peak rate around 400 Hz [11].

On the other hand, the three-body capture is a multi-step process depending on the trap dynamics and on the plasma characteristics, so that detailed predictions require specific Monte Carlo calculations. One of these simulations has recently considered the antihydrogen formation in a Penning trap, assuming the ATHENA positron plasma density and geometry [15]. The simulation finds that the $\overline{\mathrm{H}}$ atoms that survive trap electrodes and e^+ plasma fields and annihilate to the trap walls have a binding energy greater than 40 K ($\simeq$ 3.5 meV). Although no $\overline{\mathrm{H}}$ production rate is calculated, there is a qualitative agreement between some predictions of this model and the ATHENA results: the antiatom yield is predicted to be around 33% to be compared to the observed one of 15-17% [8] (see also tab. 1), and a large fraction of antiatoms have greater than thermal velocity, as we recently reported in [16]. Indeed, using the antihydrogen annihilation detector, experimental evidence that the spatial distribution of the emerging antihydrogen atoms is independent of the positron temperature and axially enhanced was obtained [16]. This indicates that antihydrogen is formed before the antiprotons are in thermal equilibrium with the positron plasma. Using a model in which $\overline{\mathrm{p}}$ s rotate with the positrons and homogeneous formation is assumed, a lower limit of 150 K for the axial temperature of the antihydrogen atoms was obtained.

In spite of these first analyses, a lot of furhter theoretical work is needed to clarify many questions concerning the production mechanisms, rates, temperature dependence and the final state distribution of the antihydrogen atoms produced. Due to the complexity of the problem, a complete simulation taking into account the three-body reaction, spontaneous radiative recombination, collisional excitation and de-excitation, radiative de-excitations and ionization of the formed atoms, giving predictions to be compared with our results [8, 11], is still missing.

During 2004 data taking the experimental apparatus was modified to allow the insertion of a laser light into the mixing trap to stimulate the radiative formation of antihydrogen in the $n = 11$ quantum state. A CO_2 continuous wave laser was used with a tunable wavelength $9.5 < \lambda < 11.2$ μm; most of the data have been collected with $\lambda = 10.96$ μm. The beam waist in the mixing region was about 2 mm with a typical peak intensity of 160 W cm^{-2} at 10 W power. The expected stimulated formation rate with a power of 100 W/cm^2, 10^4 antiprotons and a 10^8 cm^{-3} positron plasma density, was 60 Hz under equilibrium conditions at 15 K.

Since the transition is from the continuum, the recombination rate is not affected by the finite Doppler width for T = 15 K nor by the laser band width (100 MHz), because the level population and oscillator strength are nearly constant within these widths.

With laser light into the mixing region (laser ON) a slight increase in temperature and no vacuum deterioration have been measured. Therefore, to assure the same environment conditions between laser OFF and laser ON cold mixings, comparison was made in the same mixing cycle, by chopping the laser beam at a frequency of 25 Hz, with triggers recorded by the DAQ.

The analysis of the collected data is still in progress but no obvious enhancement in $\overline{\mathrm{H}}$ production has been observed.

CONCLUSIONS

Between 2002 and 2004 the ATHENA experiment produced more than 2 million antiatoms, studying in detail the cooling process of antiprotons inside a very dense positron plasma and determining the conditions to routinely maintain an average antiatom rate of 20-30 Hz for about a minute.

Many results of crucial importance for future experiments have been obtained, such as the dependence of the antihydrogen formation on the temperature, shape and density of the positron plasma and the spatial distribution of the antihydrogen atoms leaving the potential well of the trap.

Since our data suggest that the two-body recombination could not be the main mechanism responsible for the antihydrogen formation, it is likely that many antihydrogen atoms are produced in weakly bound states. How to determine the distribution of these states and to drive the antiatoms to more deeply bound states suitable for spectroscopy are the open challenges for the next generation experiments.

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