Cold Antihydrogen at ATHENA:Experimental Observation and Beyond

C. L. Cesar[1], M. Amoretti[2], G. Bonomi[3], P.D. Bowe[4], C. Canali[2,5], C. Carraro[2,5], M. Charlton[6], M. Doser[3], A. Fontana[7,8], M. C. Fujiwara[9], R. Funakoshi[9], P. Genova[7,8], J. S. Hangst[4], R. S. Hayano[9], I. Johnson[10], L. V. Jørgensen[6], A. Kellerbauer[3] , V. Lagomarsino[2,5], R. Landua[3], E. Lodi Rizzini[11], M. Macri[5] , N.Madsen[4], D.R.J. Mitchard[6], P. Montagna[7,8], H. Pruys[10], C. Regenfus[10], A. Rotondi[7,8], G. Testera[2], A. Variola[2], L. Venturelli[8,11], D. P. van der Werf[6], Y. Yamazaki[9], N. Zurko[8,11]

(ATHENA Collaboration)

[1]Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 21941-972, Brazil
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy
[3]EP Division, CERN, CH-1211 Geneva 23, Switzerland
[4]Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark
[5]Dipartimento di Fisica, Universitá di Genova, 16146 Genova, Italy
[6]Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK
[7]Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy
[8]Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy
[9]Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
[10]Physik-Institut, Zürich University, CH-8057 Zürich, Switzerland
[11]Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali, Università di Brescia, 25123 Brescia, Italy

Abstract. Antihydrogen atoms may become the easiest and most precise way to probe deeply into tests of violation of the CPT (charge conjugation, parity, time reversal) symmetry and the Weak Equivalence Principle (WEP). We review the first production of cold antihydrogen atoms within the ATHENA/AD-1 experiment[1] at CERN, its motivations and studies henceforth. The ATHENA success was followed almost immediately by the ATRAP group[2]. From the initial claim of production of tens of thousand of these exotic species - by the mixing of cold and trapped positrons and antiprotons - we have evolved to better understand and control the system. The joint production for 2002 and 2003 has been re-evaluated to about one million antiatoms[3]. We have performed cooling efficiency studies of antiprotons within the positron cloud[4]; developed ways to excite and heat the positron cloud, and probe its number, density and temperature *in situ*[5]; developed antiproton and antihydrogen imaging tomography[6]. We have also been able to gather information on the velocity of the formed antiatoms[7]. A large uncertainty and lack of control remains over the formation process - as revealed by its measured temperature dependence[8] - and the quantum number distribution of the population. We discuss various aspects of our findings below as well as future prospects for physics tests with antihydrogen.

Keywords: particle traps; trapped ions; hadronic atoms.
PACS: 52.27.Jt, 36.10.-k, 39.10.+j

CP770, *Atomic Physics 19,* edited by L. G. Marcassa, K. Helmerson, and V. S. Bagnato

INTRODUCTION

The lack of observable antimatter celestial bodies in the Universe - despite the searches for strong positron-electron annihilation gamma ray emission areas, and including recent and future direct search for anti-alpha particles outside the Earth's atmosphere[9] - put in check the Big Bang theory as the measured value for CP violation is inconsistent with our Universe according to present knowledge. Furthermore, despite intense efforts to find a theory of Quantum Gravity, it still remains an elusive goal. So far, no gravity waves have been detected either. From the purely experimental view, it is troubling to note that no experiment on the effect of Earth's gravity on antimatter has ever been performed, as attempts with charged particles were not possible. This evident asymmetry between matter and antimatter in the Universe is quite troublesome and our quest is to search for the origins of this by pursuing high-precision tests of CPT symmetry and WEP.

These motivations make it more than worthwhile to pursue an experiment where atoms and antiatoms of hydrogen can be compared to a high precision, searching for subtle asymmetries between matter and antimatter. The technical side is another encouraging aspect. Despite the quotation[10] by D. Kleppner in 1992 at the antihydrogen workshop that “In the past 6 years, the creation of antihydrogen has advanced from the totally visionary to the merely very difficult’’, much had advanced by the time ATHENA was formed. Particularly encouraging was the previous work with antiprotons[11,12] and the then recent trapped hydrogen spectroscopy[13]. Also, in 2000, the group of T. Hänsch, in Garching and coworkers from Paris, were able to measure the 1S-2S transition to an unprecedently high precision, with 14 decimal places[14]. These techniques together with the results in positron accumulation[15] prompted the beginning of this new experiment[16] under the newly create AD (Antiproton Decelerator), which took over the role of LEAR after its closure in 1996, at a much lower operating cost.

THE APPARATUS

The ATHENA apparatus has been described in lengthy detail in a NIMA paper[17]. For the purpose of this brief description it can be divided into modules. (i) the antiproton catching, cooling and accumulation trap; (ii) the positron source and accumulator; (iii) the nested Penning trap where antiprotons and positrons are held and combined to form antihydrogen, and (iv) the detector, which detects the charged pions and gamma rays from the annihilation of antiprotons and positrons. Of course, there is a whole support computer control for the experimental sequence and a series of analysis software packages and Monte Carlo tools. An overview of the apparatus is shown in Fig. 1.

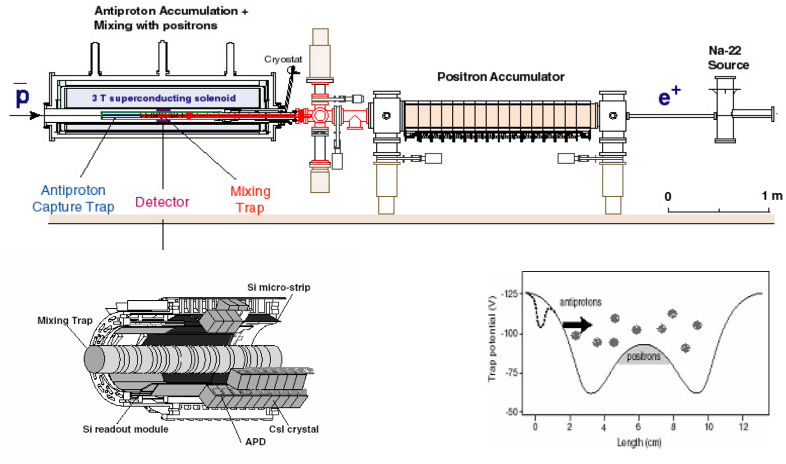

FIGURE 1. Upper: overview of the ATHENA apparatus. Antiprotons (pbars) delivered from CERN's AD enter the 3 T Penning trap where they are caught, electron cooled and stored. A ^{22}Na positron source has a solid Ne film at its surface. The positrons (e^+) are guided and accumulated at the positron accumulator and later transferred into the mixing trap, which is surrounded by the detector, shown in the lower left part. Lower right: once the two species are in the nested Penning trap the antiprotons are released into the positron plasma.

The antiproton catching trap, inside a 3 T superconducting solenoid, is operated in a dynamic mode. The energetic antiprotons, 5 MeV (p=100 MeV/c), delivered by the AD, at a number of about 10^7 per pulse every 100 s, are first slowed down through moderators (about 240 μm silicon equivalent), in which a large fraction stop and annihilate. The surviving antiprotons travel down the trap and those with kinetic energy (along the axis) < 5 keV are reflected by the –5 kV ring electrode. Before the reflected bunch can escape back from entrance side, the entrance electrode is switched to –5 kV. From the 10^7 antiprotons per bunch from the AD, we typically catch 3 x 10^3. Before the admittance of the antiprotons, the trap is loaded with electrons which cool quickly via synchrotron radiation in the 3 T field. Through coulomb collisions, the antiprotons thermalize with the electrons such that the sample is close to the ambient temperature after a few 10's of seconds. The electrons are later ejected by a series of electric impulses to which they readily respond whilst the antiprotons, presenting much higher inertia, remain in the trap.

From the other side of the apparatus, positrons are emitted continuously from a ^{22}Na radioactive source. In a technique invented by A. Mills, a solid neon moderator is grown at the source's surface, which helps thermalizing the emitted positrons. They are then guided by magnetic fields into the positron accumulator, consisting of a Penning-Malmberg trap. The accumulator region has nitrogen buffer gas, as pioneered by C. Surko, at differential pressures and it is electrically shaped such that the trap minimum is at the best vacuum region, about 10^{-6} mbarr. Positrons transversing the trap have a high probability to undergo an inelastic collision (N_2 has a nice resonance for that) with the buffer gas, loosing energy, thereby becoming trapped. Once trapped, they undergo further collisions and eventually migrate to the trap bottom. Due to the annihilation on the gas and trap losses - as the sample gets bigger - the accumulation process saturates. By employing a rotating electric field in a split ring electrode, we can shrink the sample (through conservation of angular momentum) such that the saturation occurs at larger number. This machine, developed by the group of M. Charlton produces the highest rate of positron accumulation to date. We typically have 100 million positrons to mix with the antiprotons every 300 s.

After accumulating positrons and 3 shots of antiprotons, the positrons are transferred into the superconducting magnet, in the so called combination trap, at the side of the antiproton trap. The antiprotons are then released into the nested Penning trap (see Fig. 1, lower right), where they undergo collisions with the positrons and eventually form a bound state. The exact combination process, whether a three-body (1 antiproton and 2 positrons) process, or by spontaneous emission of a photon, or by the formation of a guiding center atom as a first step, is not known. We have evidence[8] that all these process may be happening at competitive rates. Actually, the three-body process should be happening at the highest rate. However, most of the atoms formed via this process have high quantum numbers and may be ionized as they try to escape our dense positron cloud, which just recycles the antiproton and positron back into the nested trap, until more tightly bound atoms are formed.

Once the neutral atoms are formed they are free to leave the region, and typically annihilate at the trap walls (electrodes), emitting pions and gamma rays. The walls around the nested trap are surrounded by our detector consisting of many silicon strips covering 80% of the solid angle (in a double layer configuration, one behind the other, so as allow trace reconstruction, see Fig. 1, lower left) and 192 CsI crystals for detection of 511 keV gamma rays from the annihilation of the positrons. An annihilation event of an antihydrogen atom would lead to the simultaneous production of 3 or more pions – due to the antiproton annihilation - and 2 or more gammas, due to the slow positron annihilation. The pions' tracks are calculated and an annihilation vertex is determined, that is, the antiproton annihilation is imaged. A reconstructed event is used for antihydrogen detection if, within the same time window (about 5 μs), the detector only has two crystals lit, excluding the crystals on the pion track. In this case this event will be registered including the position and time of the annihilation as well as the lit crystal's numbers, which allow us to find the opening angle, from the annihilation vertex, to the two lit crystals. A golden event would have the supposed 2 gamma rays emitted from the positron annihilation in a back to back configuration, making this an opening angle of 180^0 $\cos(\theta_{\gamma\gamma}) = -1$. By constructing a histogram of events as function of the opening angle, one can clearly differentiate, in a statistical manner, antihydrogen annihilation from pure antiproton annihilation, or other background process. An excess of entries in the histogram's bin corresponding to this opening angle of 180^0 is a clear signature of antihydrogen formation.

RESULTS

Six years after the beginning of ATHENA we found the first clear signal for antihydrogen production. This is presented in Fig. 2 below, showing the excess count at the bin $\cos(\theta_{\gamma\gamma}) = -1$. A preliminary analysis led to the claim that we had produced 50,000 atoms.

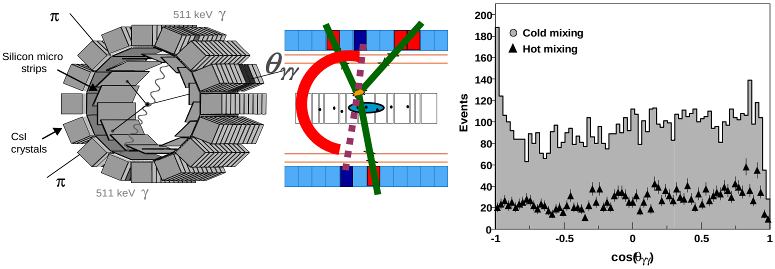

FIGURE 2. Left: the detector and the traces (pions and gammas) from a fictitious annihilation event. Middle: 2-d view of the hits in the silicon strips, the reconstructed vertex and the opening angle $\theta_{\gamma\gamma}$ between the two 511 keV gammas. Right: the detection of antihydrogen showing excess counts around $\cos(\theta_{\gamma\gamma}) = -1$. The black dots histogram appears when the positron cloud is heated by resonant RF, which has the effect of suppressing antihydrogen (no excess counts are observed near $\cos(\theta_{\gamma\gamma}) = -1$ as expected from the formation processes as the positrons are moving quite fast). From Ref. 1.

In the last 2 years we have studied the system in greater detail. By looking at the spatial distribution of the annihilation signal, accompanied by a Monte Carlo analysis (see Fig. 3) and studying the formation time dynamics, together with the opening angle histogram we have improved our knowledge of the system. We have shown that over the full 180 s mixing cycle, about 60-70% of all event triggers are, under the right conditions, due to antihydrogen formation[3].

Reviewing the detection efficiencies we have concluded that we formed about 1 Million antihydrogen atoms in the 2003-2004 period. A future magnetic trap for the neutrals would only capture the low kinetic energy atoms. Therefore, it is important to have a large number of atoms, so as to be able to capture a reasonable number from the low energy tail of its distribution.

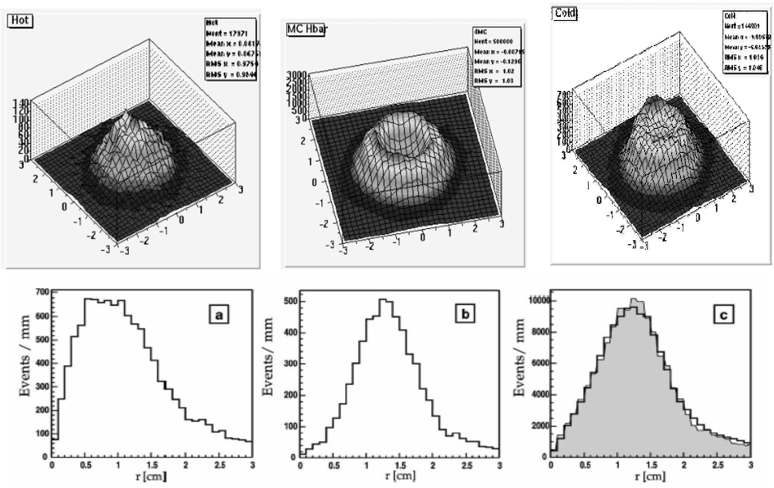

FIGURE 3. A comparison of “images” of vertex reconstruction between a (a) “hot mixing”, (b) a Monte Carlo simulation of cold mixing, and (c) “cold mixing” superimposed onto a Monte Carlo curve showing excellent agreement. In hot mixing, the positron cloud is heated to thousands of degrees by resonant RF, thus suppressing the formation of antihydrogen, resulting in annihilation with the background gas in the center of the cell. In cold mixing, most annihilations stem from antihydrogen annihilating at the trap walls.

A study of the escape velocity of the anithydrogen has been recently accepted for publication[7] and it shows evidence for a reasonably high speed (higher or of order of 1000 m.s^{-1}) which could present serious difficulties for the magnetic trapping of these neutrals. A major issue is the rotation of the antiprotons together with the positrons as the **E** x **B** term dominates the dynamics, once the antiprotons come close to equilibrium within the positron cloud. This rotation represents a high speed at the plasma’s edge. By looking at the annihilation position of the atoms in the wall we have been able to extract typical axial velocities of the atoms as the annihilation point depends only on the ratio of the axial to the radial velocities. The axial velocity seems to be higher than its radial counterpart, implying a leftover kinetic energy from the antiproton’s release process, originally at tens of eV. This finding may have implications for future mixing techniques. A possible solution to this is to send the positrons through the cold antiprotons.

During 2004 we tried to achieve laser induced combination, using a high-power CO_2 laser, which would stimulate the formation of atoms at the principal quantum number n = 11. The data is still under analysis, but due to a series of problems with the apparatus, including the AD, it seems unlikely that we have succeeded in finding a convincing signal of this process.

PROSPECTS

Superimposing a Ioffe-Pritchard magnetic trap with the nested Penning trap would, in principle, allow trapping of the low energy (δ1 K) neutral atoms. On the other hand, there is a long running discussion as to whether the positrons would survive this combination of fields. This issue is still subject to discussion and new results should be available soon[18]. If it is not feasible to use a quadrupolar field, it should be possible to employ a higher multipole for this task. Supposing one is able to address this problem and eventually trap a small number of atoms at the ground state and at an energy of about 1 K (which requires about 1.5 T of magnetic field trap depth), it is impressive that just a few atoms detected via laser spectroscopy on the 1S-2S transition would lead to a comparison precision of parts in 10^{10}, as we show below.

The main broadening and uncertainty mechanisms in the spectroscopy of the $1S_d$ - $2S_d$ transition are[19] (i) the Zeeman effect, given by

$$\Delta\omega_{B\ Shift}/2\pi = 180\ [B/1\ tesla]\ kHz \quad (1),$$

and (ii) the time-of-flight broadening through a finite laser beam waist w_0, given by

$$\Delta\omega_{tof} = 2 \ln 2\ v_{r0}/w_0 \sim 2\pi.280\ [T/1K]^{1/2}[0.1\ mm/w_0]\ kHz \quad (2).$$

If we suppose a 1 K sample, the B-field shift and broadening would be about 0.3 MHz. With a 0.1 mm laser waist, the time-of-flight broadening would be about the same value. Therefore, for a single atom detected the uncertainty - which scales typically as $N^{-1/2}$, N being the number of atoms detected – would be about 0.4 MHz, which represents a fractional uncertainty of just 1.6 parts in 10^{10}. In order to push the precision further we will need to further cool the sample. Analysis on hydrogen[19] shows that indeed a very high precision measurement (better than parts in 10^{15}) of this transition is possible if the system is really cold, in the tens of μK regime. Since detection of antihydrogen is much easier than that of hydrogen, we claim it is possible to "see" a small number of these exotic atoms.

Without a large number of very cold atoms, employing known techniques of atom interferometry for a direct detection of the Earth's gravitational effect would be almost impossible. However, a simple ballistic measurement to see whether the Earth's gravitational effect upon antimatter is of the same order as with matter may be feasible[20].

CONCLUSION

In conclusion we have produced a large number of the first cold antihydrogen atoms. These atoms are not readily suitable for high precision measurements on CPT violation or violation of the Weak Equivalence Principle, but it represents a major first step and breakthrough. Despite ignorance of the quantum number distribution, and the exact formation process, we are confident that a new apparatus would allow for trapping of some of these antiatoms. The case is made for the feasibility of high precision comparison of the 1S-2S transition frequency between the two conjugate species even with the detection of just a handful of antiatoms. While the first step was a breakthrough, it seems that the next steps are harder. Nonetheless, nature, seemed to smile at us – our antihydrogen formation rate was better than our estimated rate of 1 Hz, in a clear violation of Murphy's law - and there is no reason to not be hopeful of the same for the future steps. Of course, we will have to be quite resourceful and the invention of new techniques will be necessary for this enterprise to succeed. The importance of the issues tested ensure continuous motivation for this.

REFERENCES

1. M. Amoretti *et al*. (ATHENA COLL.), Nature **419**, 456 (2002)

2. G. Gabrielse *et al*., Phys. Rev. Lett. **89**, 213401 (2002)
3. M. Amoretti *et al*. (ATHENA COLL.), Phys. Lett. B **578**, 23 (2004)
4. M. Amoretti *et al*. (ATHENA COLL.), Phys. Lett. B **590,** 133-142 (2004)
5. M. Amoretti *et al*. (ATHENA COLL.), Phys. Rev. Lett. **91**, 055001 (2003); Phys. Plasmas **10**, 3056 (2003)
6. M. Fujiwara *et al*. (ATHENA COLL.), Phys. Rev. Lett. **92**, 065005 (2004)
7. N. Madsen *et al*., Phys. Rev. Lett., accepted
8. M. Amoretti *et al*. (ATHENA COLL), Phys. Lett. B, **583**, 59 (2004)
9. AMS Collaboration *et al*., Phys. Rep. **366/6,** 331 (2002)
10. D. Kleppner, Hyp. Interact. **76**, 389 (1993)
11. G. Gabrielse *et al*., Phys. Rev Lett. **74**, 3544 (1995)
12. M. H. Holzscheiter, Phys. Scripta T **59**, 326(1995)
13. C. L. Cesar *et al*., Phys. Rev. Lett. **77**, 255 (1996)
14. M. Niering *et al*., Phys. Rev. Lett. **84**, 5496 (2000)
15. C. M. Surko, R.G. Greaves and M. Charlton, Hyp. Interact. **109**, 181 (1997) and references therein
16. M.H. Holzscheiter et al., Hyp. Interact. **109**, 1, (1997)
17. M. Amoretti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **518**, 679 (2004)
18. J. Fajans, *et al*., submitted to Phys. Rev. Lett.
19. C.L. Cesar, MIT PhD thesis (1995), unpublished; C.L. Cesar and D. Kleppner, Phys. Rev. A **59**, 4564 (1999); C.L. Cesar, Phys. Rev. A **64**, 023418 (2001)
20. C.L. Cesar, Hyp. Interact. **109**, 293 (1997)