

Recent Results of the ATHENA Collaboration

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Abstract. The ATHENA/AD-1 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 briefly recalled. Emphasis is put on the results of 2006 with reference to the papers published or in press.

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

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1. INTRODUCTION

In 2002 two experiments at CERN, first ATHENA [1] and then ATRAP [2], reported the production of cold antihydrogen (\bar{H}) by mixing antiprotons and positrons at low temperature in a nested Penning trap [3]. The ultimate goal of these experiments is to test matter-antimatter (CPT) symmetry by means of high precision two-photon spectroscopy of the \bar{H} $1S$ - $2S$ transition, and hence the development of methods to enhance the production of cold, ground-state \bar{H} atoms is of great importance.

The ATHENA apparatus [4] used 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{p} s and the positrons were trapped, cooled and accumulated in separate traps prior to moving and mixing in a common trap (called the *mixing* trap) in the central region. The positron accumulation trap was located inside a room temperature vacuum chamber in a 0.14 T magnetic field. The antiproton capture trap and the mixing trap were located in the 3 T field of a superconducting magnet whose bore was kept at 130 K under normal operation. A liquid-helium cryostat reduced the temperature of the trap region to about 15 K. Ultra-high vacuum conditions were also provided. The 3 Tesla solenoidal magnetic field provided the radial confinement and also allowed 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 \bar{H} atoms surviving collisions and field ionization escape the confinement region and annihilate on the trap electrodes producing a signal in the surrounding vertex detector [5] that triggers the detector readout (efficiency of 85 ± 10 %). The decay products of the annihilations (charged π s from the \bar{p} , γ s from the e^+) are then reconstructed, making possible the three-dimensional imaging of antiproton and positron annihilations in the Penning trap [6, 7].

After three years of running, ATHENA finished data taking in 2004. In this final report, which completes that of January 2006 [8], we briefly recall and comment the main results obtained, with reference to the papers published in the recent months.

2. SUMMARY OF THE RESULTS

After having found the optimum conditions to proceed routinely [1, 6], in 2003 ATHENA studied systematically the dependence of the antihydrogen production on the temperature and on the shape of the positron plasma [9, 10, 11, 12].

In [13] 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 \bar{H} for tens of seconds.

In [9] we measured, for the first time, \bar{H} production as a function of the positron plasma temperature from 15 K up to more than 3000 K.

The antihydrogen production is observed to decrease with increased positron plasma temperature, as expected (this effect was used in previous work to suppress the antihydrogen formation [1]), but 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).

Some attempt has been made to analyze these results in terms of the two main processes that are involved in the \bar{H} formation: the *two-body radiative capture* ($e^+ + \bar{p} \rightarrow \bar{H} + \gamma$) and the *three-body combination* ($e^+ + e^+ + \bar{p} \rightarrow \bar{H} + e^+$).

However, all the efforts to fit the data with combinations of power laws, e.g. representing a mixture of two- and three-body processes, are unsuccessful. The naive scaling for the three-body reaction, $T^{-9/2}$, is clearly inconsistent with our data. It should be noted that collisional relaxation and finite transit time of the antiprotons through the positron plasma can lead to a different temperature scaling for the three-body reaction

[14, 15, 16].

Following simple assumptions, the peak trigger rate, defined as the maximum value of the detector trigger rate after the start of mixing, should be comparable to the rate due to the radiative combination; given a temperature of 15 K, and assuming complete overlap between the two particle clouds, we calculated an antihydrogen production rate of about 40 Hz for 10000 \bar{p} s and $1.7 \times 10^8 \text{ cm}^{-3}$ positron plasma density. If we compare this value with our measured value of $432 \pm 44 \text{ Hz}$ [9] we clearly see that the experimental result is one order of magnitude higher. In other words the absolute measured production rate is not obviously compatible with a simple radiative calculation.

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 [14]. The simulation finds that the \bar{H} atoms that survive trap electrodes and e^+ plasma fields and annihilate on the trap walls have a binding energy greater than 40 K ($\simeq 3.5 \text{ meV}$). Although no \bar{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% [6], and a large fraction of antiatoms have greater than thermal velocity.

This last fact is in agreement with an analysis that we recently reported in [17], where, 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.

In an effort to clarify the situation, we have also investigated the radiative \bar{H} formation mechanism by attempting to stimulate capture using laser light [18].

The analysis of these data show a null laser effect on \bar{H} production. Barring the unlikely possibility of a suboptimal overlap between the antiprotons and the laser beam, this result suggests that spontaneous two-body radiative formation in conditions of thermal equilibrium gives a negligible contribution to the \bar{H} formation in the ATHENA nested trap. This conclusion is in agreement with the ATHENA results previously considered, showing that the \bar{H} formation does not occur under conditions of thermal equilibrium between the \bar{p} and the e^+ [9, 17]. Therefore, it is likely that three-body capture and collisional processes are the dominant mechanisms.

Besides the \bar{H} formation followed by the annihilation on the trap *wall*, in our experimental conditions, for both the cold and hot mixing samples, we observe around 10^2 annihilations per \bar{p} injection cycle in the trap *volume*, one order of magnitude less than the \bar{H} formed in cold mixing.

An analysis of these annihilation events has shown their full consistency with a model that assumes protonium formation through the reaction $\bar{p} + H_2^+ \rightarrow (\bar{p}p) + H$ on the residual ionized gas of the trap [19]. The protonium lifetimes are found to be equal in the 'cold' and 'hot' samples, within the experimental resolution.

Therefore we have demonstrated the possibility to produce metastable protonium in a near-vacuum condition. The kinetic energies are in the range $40 \div 700 \text{ meV}$. The measured lifetime of $1.1 \mu\text{s}$ and the absence of recoil suggest a protonium formation in a $n \simeq 65$ state with low orbital angular momentum ($l < 10$) [20]. This opens the possibility for a new class of experiments using protonium as a probe of fundamental

constants and symmetries [22].

3. CONCLUSIONS

In summary, many relevant results, useful also as guidelines for future experiments, have been obtained, such as:

- the determination of \bar{H} production rates and yields as a function of some standard mixing conditions [1, 6];
- the observation, for the first time, of the distribution of the particle loss in a Penning trap by reconstructing the annihilation vertices from the trajectories of the charged annihilation products [4, 7];
- the study of the time evolution of the \bar{p} cooling process, with the identification of several distinct types of behaviour [13];
- the dependence of the \bar{H} formation on the temperature and shape of the positron plasma [9, 10, 11, 12];
- the spatial distribution of the antihydrogen atoms leaving the potential well of the trap, and the determination of the \bar{H} axial temperature [17].

During 2006 we published results on:

- some techniques of \bar{p} cooling [21];
- the use of a laser to induce the formation of antihydrogen atoms with principal quantum number $n=11$ [18];
- the analysis of our background in terms of a protonium formation model [19];
- the dependence of \bar{H} formation on the e^+ plasma control techniques (in preparation).

To conclude the analysis of our data and to complete the ATHENA mission, we plan to finish the paper in preparation and to make a final reanalysis of all the data, to present all the ATHENA activities and results in a general paper.

Finally, we want to remark that the important issue of the quantum states of the formed \bar{H} still remains an open problem. However, the ATHENA results will provide a sound basis for the search at AD for new, efficient methodologies for the production of cold ground state antihydrogen.

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