Production and Detection of Cold Anti-Hydrogen Atoms. A First Step Towards High Precision CPT Test

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Abstract.
Observations of anti-hydrogen in small quantities have been reported at CERN and at FermiLab, but these experiments were not suited to spectroscopy experiments. In 2002 the ATHENA collaboration reported the production and detection of very low energy anti-hydrogen atoms produced in cryogenic environment. This is the first major step in the study of antiatom's internal structure and it can lead to a high precision test of the CPT fundamental symmetry. The method of production and detection of cold anti-hydrogen will be introduced. The absolute rate of anti-hydrogen production and the signal to background ratio in the ATHENA experiment will be discussed.

Testing fundamental symmetries is of great interest in modern physics. A major role is played by the tests of the CPT theorem which ensures the physical invariance of systems simultaneously subjected to charge conjugation, parity inversion and time reversal. This happens for point particles in a flat space-time under the assumptions of Lorentz invariance and unitarity. Different theories that are not based on these assumptions suggest CPT violations. The one put forward by Colladay and Kostelecky[1] is worth mentioning. Another CPT violation mechanism has been suggested by Ellis et al. [2] who invoke quantum gravity.

Why antihydrogen?

A number of measurements have already been carried out as CPT tests comparing the characteristics of particles with those of antiparticles. The precision attained in the neutron kaon mass measurement (10^{-18}) is impressive, even though it was obtained in a the-

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oretically dependent manner. In future an high degree of precision could be obtained in a direct measurement by means of the spectroscopy of antihydrogen atoms in the 1S-2S transition [3]. The first antihydrogen atoms formed in flight have been detected at CERN [4]. Their low number and high velocity made them unsuitable for spectroscopy which requires a high number of antiatoms at low temperatures. Cryogenic temperatures are needed for three main reasons: the inverse dependence of temperature on radiative and three-body recombination; the inverse dependence of velocity for neutral atom trapping; the Doppler effect determining the ultimate resolution of the spectroscopy measurement. In the summer of 2002 the ATHENA experiment made a first breakthrough producing and detecting a large quantity of antihydrogen atoms at cryogenic temperatures [5]. The experimental apparatus, the technique used for antihydrogen production and detection, as well as the first experimental results are illustrated in this paper.

The ATHENA experiment

The Athena apparatus is made up of three main devices, each performing a specific function: the main cryostat, the positron accumulator and the antihydrogen detector. In the main cryostat antiprotons are caught, cooled, transferred and mixed by means of Penning Malberg traps. Bunches of some 10^7 antiprotons are supplied by the CERN AD facility [6] in cycles of ~ two minutes at ~ 5 MeV energy. Once extracted, they are injected into the main cryostat where a 3T solenoidal magnetic field is imposed for the radial confinement of charged particles. The low energy tail is subsequently trapped in the so-called catching trap by means of a high voltage switch. Once caught, the antiprotons are cooled by means of collisions with a preloaded electron cloud. The energy released by antiprotons to the electron cloud is rapidly radiated ($\tau \sim$400 msec) by cyclotron radiation into the 3T magnetic field. At the end both the $\bar{p}$s and the electron populations reach the thermal equilibrium with the cryogenic environment. The cooled antiprotons are then transferred into the so-called mixing trap where recombination takes place. The efficiency of all these processes is relatively low and in the end roughly 10000 antiprotons are injected in the mixing cycle for recombination. The mixing trap electrodes' arrangement allows a nested potential configuration (see fig. 1). This configuration allows for the simultaneous axial confinement of oppositely charged particles The antiprotons injected in the nested trap's outer well cross the positrons and cool, thus starting the interaction

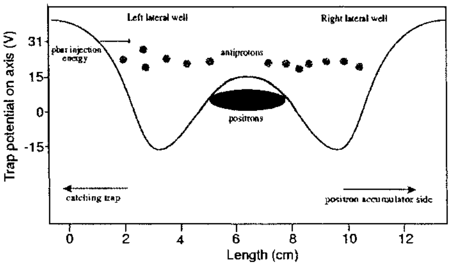

FIGURE 1. Nested potential configuration for the simultaneous axial confinement of $\bar{p}$s and positrons. $\bar{p}$s are injected at high energy and passing through the positron cloud they cool down. Once thermalized, they diffuse into the positron plasma increasing the probability of recombination.

process which leads to recombination. The positron plasma utilized for recombination is originally produced in the positron accumulator. A radioactive Na^{22} source emits positrons, which are then cooled by collisions with a buffer gas in differential pressure sections. The positron accumulation process continues for about two minutes. At the end roughly $1.5 \cdot 10^8$ e^+ are ready to be transferred to the mixing region with an efficiency of about 50 %. The final result is a plasma of $\sim$ 75 million positron ready for recombination. Plasma characteristics such as radius, density and temperature are monitored by an innovative diagnostic system [7]. The antihydrogen atom, which is electrically neutral, is no longer confined once the recombination has taken place. Therefore, it drifts toward the trap walls causing the simultaneous and localized annihilations of both the antiproton and the positron. The antiproton-proton annihilation produces mainly pions, whereas the positron-electron annihilation provides two characteristic back-to-back 511 keV photons. They are all detected by an innovative antihydrogen detector operating in a cryogenic environment at $\sim$ 140 K. Two layers of doubled sided silicon micro strip detectors are used to localize the vertex of the charged pions tracks (fig. 2). A microsecond window is provided for the coincidence of the two back-to-back 511 keV photons from the e^+-e^- annihilation with the associated vertex.. The gammas are identified and the energy measured by means of an external layer of CsI crystals read out by APD's.

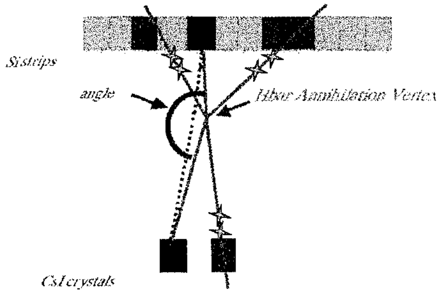

FIGURE 2. Identification of $\bar{H}$. The drawing shows the meaning of the opening angle. If Cos(θ) = -1 the vertex and the two 511 keV line are collinear.

Antihydrogen identification: experimental results

Events associating a vertex with a back-to-back 511 keV signal are plotted in a histogram illustrating the cosine of the opening angle θ. This is the angle that is subtended from the vertex to the geometrical center of the two crystals identifying the two 511 keV gamma lines (see fig. 2). The antihydrogen "golden events" are obtained for Cos(θ)=-1 i.e when there is a perfect overlap between the vertex and the back to back 511 keV line. The events characterized by $\cos\theta \neq -1$ can still identify an $\bar{H}$ event where the vertex misalignment is possibly due to background or noise events. A full Monte Carlo simulation that takes into account the showers produced in the magnet coils has modeled this. The measurement results are shown in fig. 3 a,b. In fig. 3a the continuous line represents the spectrum when the mixing takes place at cryogenic temperature (cold mixing). The cos $\theta=-1$ peak is the signature of antihydrogen. The rest of the spectrum is partially composed by the $\bar{H}$ signal and the background. To rule out any possible misleading mechanism in antihydrogen detection in-depth background studies and measurements have been carried out (see fig. 3 a, b). In fig. 3a the triangles show the

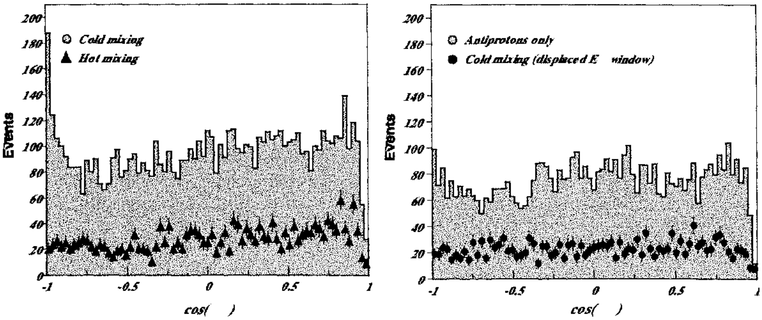

FIGURE 3. The experimental results proving antihydrogen production are displayed

spectrum acquired when the positron plasma was heated by applying RF (hot mixing). In fig. 3b the continuous line illustrates the spectrum resulting from the annihilation of $\bar{p}$s in the absence of positrons, whereas the circles show the cold mixing results when the crystal energy window is shifted away from the 511 keV range. In all three cases the absence of the $\cos\theta = -1$ peak is noticeable. This is the final and decisive evidence of antihydrogen atom production. Considering only the so-called golden events, at least 50000 antihydrogen atoms have been produced, but the analysis of the signal to background ratio shows that the production is much larger, which will be the subject of a forthcoming publication. Our heating techniques and the use of the detector have enabled us to assess the production dependence on temperature and the spatial distribution of the $\bar{H}$s produced. These results are also under study and will be submitted for publication.

Conclusions

In this article the main recent results of the ATHENA collaboration have been briefly summarized. The importance of antihydrogen physics in relation to the CPT tests has been highlighted. The experimental apparatus and the techniques used have been rapidly shown. The criteria for antihydrogen identification and the experimental results that have enabled us to provide strong evidence of the first production of antihydrogen atoms at cryogenic temperature have been illustrated. The next goal of the ATHENA collaboration is the detailed study and characterization of the antihydrogen produced. Therefore the production rate needs to be optimized to allow for the first interaction between anthydrogen atoms and laser.

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