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Temperature dependence of anti-hydrogen production in the ATHENA experiment

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Abstract

The ATHENA experiment recently produced the first sample of cold anti-hydrogen atoms by mixing cold plasmas of anti-protons and positrons. The temperature of the positron plasma was increased by controlled RF heating and the anti-hydrogen production rate was measured. Preliminary results are presented.

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1. Introduction

Cold anti-hydrogen ($\bar{\mathrm{H}}$) atoms have been recently produced by two experiments at CERN. First the Athena collaboration [1] and, a few

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months later, the Atrap collaboration [2] reported the creation of samples of cold anti-hydrogen by mixing anti-protons with positrons. There are two main processes that can lead to the production of $\bar{\mathrm{H}}$ [3–5] through mixing: the so-called *radiative recombination* in which a photon carries away the binding energy plus the kinetic energy of the positron in the anti-atomic center of mass frame, and the so-called *three body recombination* in which a second positron carries away the excess energy and momentum. The two mechanisms predict different $\bar{\mathrm{H}}$ n-state distributions and a different production rate dependence on the positron plasma density and temperature ($T^{-1/2}$ [3] and $T^{-9/2}$ [4], respectively). We here assume that the positron plasma is in thermal equilibrium and the relative velocity between positrons and anti-protons is represented by the plasma temperature. In the Athena experiment we have been able to change the positron plasma temperature and to measure the induced production rate changes. A preliminary analysis, assuming a power law rate dependence T^{α}, yields $-0.5 < \alpha < -1.5$. However, this result is only a first step to answering the question about the relative contributions of radiative and three body recombination.

2. The analysis

2.1. Introduction

The standard mixing cycle procedure in the Athena experiment is the following (see Fig. 1) we fill the central part of a nested trap [6] (a configuration that allows simultaneous trapping of opposite charge particles) with about 7×10^{7} positrons, we wait for the positrons to cool down, then we inject about 10 000 anti-protons and allow the two species of particles to interact for about 3 min. Then we empty the nested trap and we restart the process. In the mixing region the necessary experimental conditions for making anti-hydrogen, such as cryogenic temperature (~15 K), very low pressure (<10^{-12} mbar) and high magnetic field (3 T), are provided by our experimental apparatus. The nested trap is surrounded by our anti-hydrogen detector [7]. In a homogeneous magnetic field electrically neutral $\bar{\mathrm{H}}$ atoms escape the confinement region and annihilate on the trap electrodes producing on average about five pions (charged and/or neutral) and two 511 keV γs. The detector is designed to track charged particles for vertex reconstruction and to measure the position and energy of the 511 keV γs. See Fig. 2 for a schematic view of an $\bar{\mathrm{H}}$ annihilation detection. Charged particles are detected in two layers of silicon micro-strip detectors covering 80% of the solid angle. Photons from positron annihilation (511 keV) convert in the CsI crystals by photoelectric effect. The overall dimensions of our cylindrical detector are 75 (140) mm inner (outer) diameter and 250 mm in length.

2.2. The positron plasma temperature

The typical properties of the positron plasma are the following: length $L = 32$ mm, radius

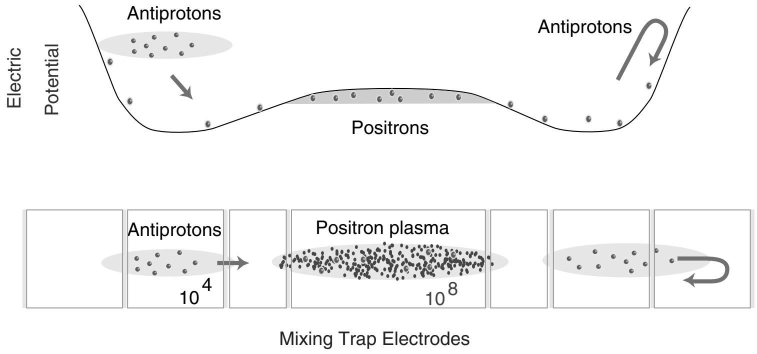

Fig. 1. Schematic drawing of the nested trap region where positrons and anti-protons are mixed.

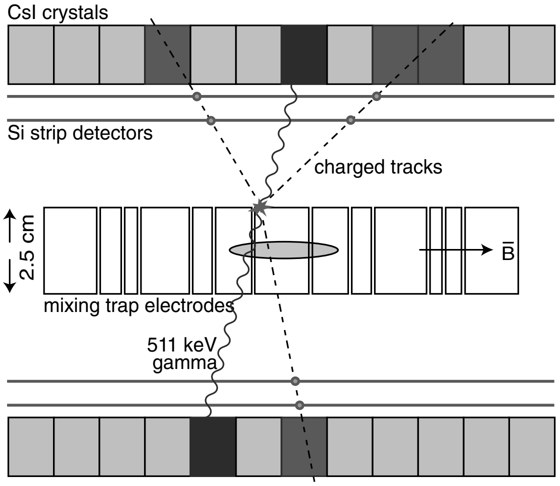

Fig. 2. Schematic view of our anti-hydrogen detector and of an $\bar{\mathrm{H}}$ annihilation detection.

$R = 2.5$ mm, number of particles $N = 7 \times 10^7$, average density $n = 1.7 \times 10^8$ cm^{-3}. A radio frequency signal (RF heating) was applied to induce a positron plasma temperature increase (ΔT). The shape, size, particle density and temperature increase of the positron plasma have been deduced using a non-destructive diagnostics method, based on the excitation and detection of the lowest (dipole, quadrupole) plasma modes [8]. We collected statistics for four different plasma temperatures: (1) no heating applied, called *cold mixing*; (2) $\Delta T = 15 \pm 15$ meV ($\simeq$175 K); (3) $\Delta T = 43 \pm 17$ meV ($\simeq$500 K); (4) $\Delta T = 306 \pm 30$ meV ($\simeq$3500 K), called *hot mixing*. We have verified that antihydrogen production and subsequent annihilation on the electrodes constitutes a significant fraction of the observed detector trigger rate. This rate indeed changes dramatically for the different positron temperatures, as shown in Fig. 3.

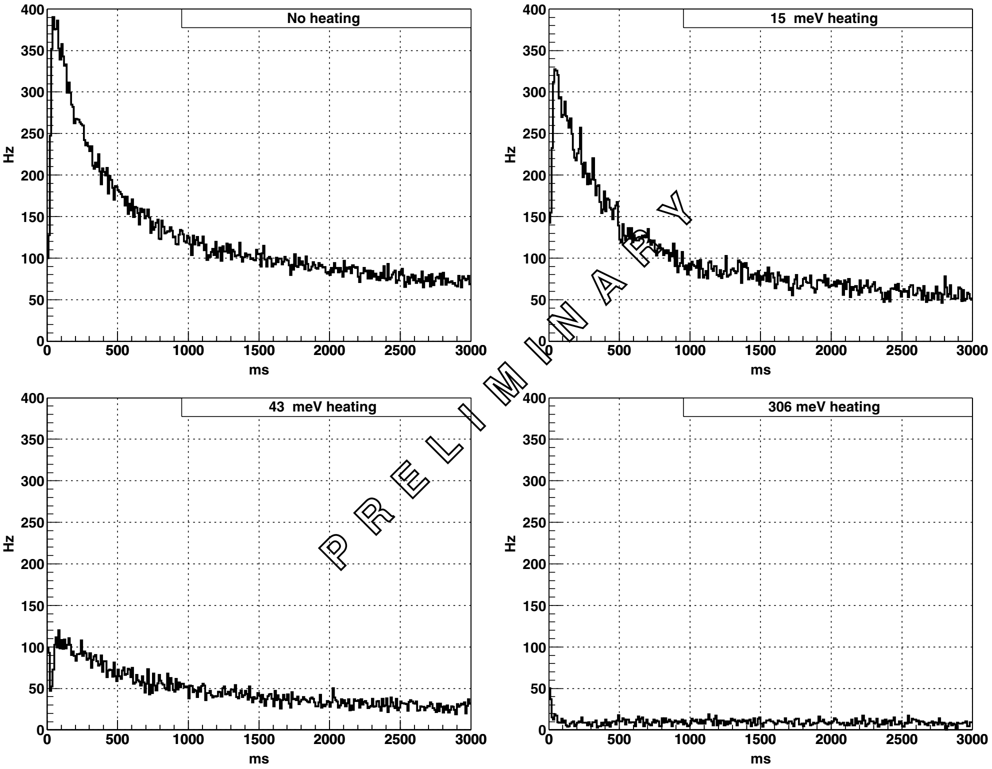

Fig. 3. Detector trigger rates for the four different positron plasma temperatures for a standard mixing cycle (all statistics scaled to one single mixing cycle).

2.3. The anti-hydrogen production

Our study of the temperature dependence of the anti-hydrogen production rate is based on the measurement of the annihilation rate and the reconstruction of annihilation events by the detector. Changes in the $\bar{\mathrm{H}}$ production as a function of the positron plasma temperature has been measured using the *opening angle excess*.

For each event with a reconstructed anti-proton annihilation vertex and two *clean* 511 keV photons (no neighbouring crystals must be hit), the opening angle between the two photons ($\theta_{\gamma\gamma}$) – as seen from the vertex – is considered. An $\bar{\mathrm{H}}$ event fully reconstructed will have an opening angle of 180°, corresponding to $\cos(\theta_{\gamma\gamma}) = -1$. The other entries stem either from uncorrelated 511 keV background due to γ conversion, and/or from the detection of only one of the two 511 keV from the Hbar event, in coincidence with a background photon. The opening angle distributions for the four different temperatures are show in Fig. 4. We call *opening angle excess* the number of events with $\cos(\theta_{\gamma\gamma}) \leqslant -0.95$ exceeding the almost flat central region plateau. Fig. 5 shows the resulting dependence of the number of excess events as a function of the plasma temperature.

We have corroborated this result using two further observable that give an independent measurement of the anti-hydrogen production rate: (1) the peak trigger rates and (2) the number of $\bar{\mathrm{H}}$ atoms produced. Method (1) is based on the observation of a dramatic and rapid jump in the rate of annihilation when anti-protons are injected into the positron plasma (see Fig. 3). The peak trigger rate is defined as the maximum number of detector triggers in the window [30–60] ms after the start of the mixing of anti-protons and positrons.

Method (2) uses four different ways to calculate the number of $\bar{\mathrm{H}}$ atoms produced in each mixing

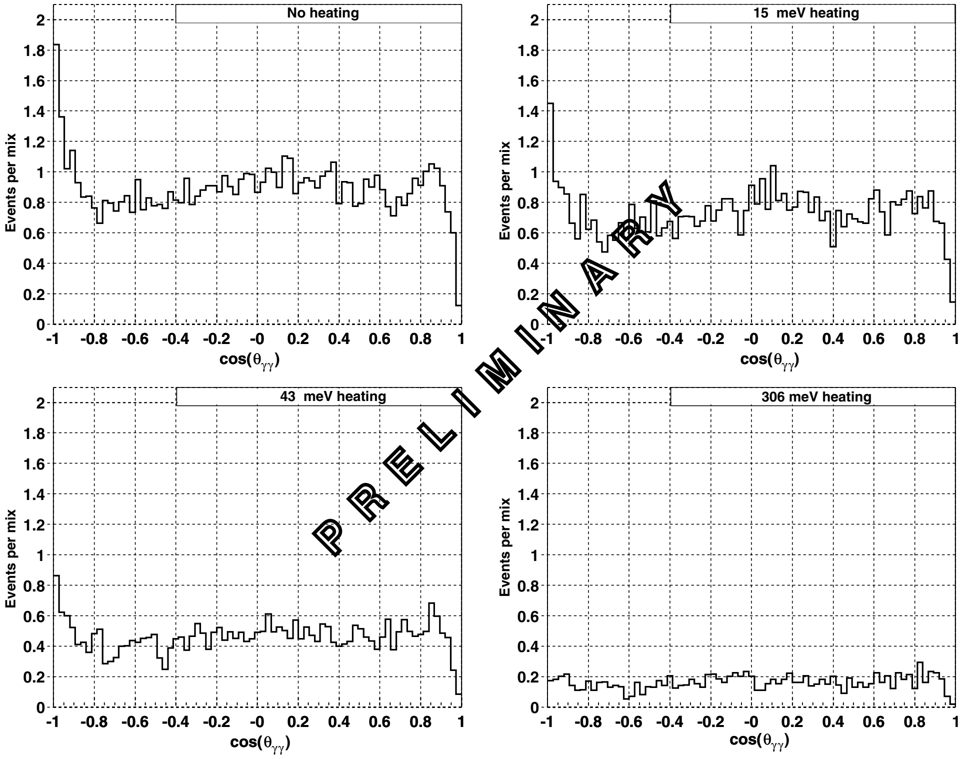

Fig. 4. Cosine of the opening angle distribution for the four different positron plasma temperatures for a standard mixing cycle (all statistics scaled to one single mixing cycle).

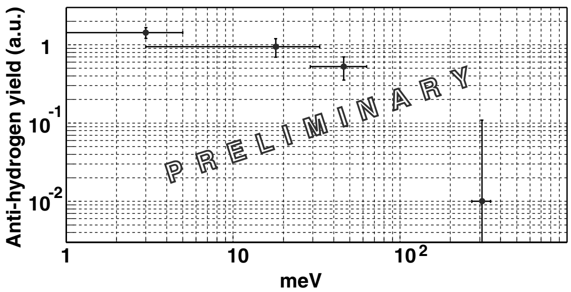

Fig. 5. Temperature dependence of $\bar{H}$ production using the opening angle excess.

cycle. In three of them we use a Monte Carlo (MC) simulation to model the $\bar{H}$ signal and the *hot mixing* data to model the background (fit of the *xy* distribution of the vertices, fit of the radial distribution, fit of the opening angle distribution). In the fourth we use the number of entries in the opening angle distribution, using the MC probabilities for an $\bar{H}$ annihilation and a $\bar{p}$ annihilation event to enter into the opening angle distribution. For both methods (1 and 2), the anti-hydrogen production rate shows a similar dependence on the plasma temperature as the one displayed in Fig. 5.

Note that the modes diagnostics we used only yields relative temperature changes (ΔT) and not the absolute temperature of the positron plasma. We estimate that the absolute temperature (T_o) of the positron plasma without RF heating is close to the ambient one. Comparing our data with the phenomenological formula $\bar{H} = c \cdot (T_o + \Delta T)^\alpha$ we can conclude that our data are compatible with an α value $-0.5 < \alpha < -1.5$. A simple power law does not seem to reproduce the temperature dependence well, and more detailed studies are needed to identify more clearly the relative contributions of the possible production mechanisms. However, it is worthwhile noting that $\bar{H}$ production is still clearly observed at room temperature.

3. Summary

The temperature dependence of the anti-hydrogen production has been studied for the first time. RF heating of the positron plasma, together with a non-destructive monitoring of the plasma parameters, has been proven to be a new method to study the production mechanism. The anti-hydrogen production rates have been derived using three independent measurements, yielding similar results. Anti-hydrogen production is still clearly observed at room temperature. Assuming a simple power law, the temperature dependence is approximately inversely linear, albeit with a large error bar that does not yet allow to clearly distinguish between the relative contribution of radiative and three body recombination. The analysis presented in this work is still in progress and new data will be available in the next months with the start of the 2003 AD physics program, improving the statistics in the critical temperature range. A better understanding of the temperature dependence of $\bar{H}$ production is still needed to draw any further conclusion on the production mechanism involved in the experimental conditions of the ATHENA experiment.

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