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Protonium production in ATHENA

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Abstract

The ATHENA experiment at CERN, after producing cold antihydrogen atoms for the first time in 2002, has synthesised protonium atoms in vacuum at very low energies. Protonium, i.e. the antiproton–proton bound system, is of interest for testing fundamental physical theories. In the nested penning trap of the ATHENA apparatus protonium has been produced as result of a chemical reaction between an antiproton and the simplest matter molecule, H_2^+. The formed protonium atoms have kinetic energies in the range 40–700 meV and are metastable with mean lifetimes of the order of 1 μs. Our result shows that it will be possible to start measurements on protonium at low energy antiproton facilities, such as the AD at CERN or FLAIR at GSI.

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Keywords: Protonium; Antiprotons; Hydrogen molecular ion; Antihydrogen; Penning trap

The availability of a high-quality antiproton beams at low energies delivered by the CERN antiproton decelerator (AD) to the ATHENA, ATRAP and ASACUSA experiments has permitted the routine production of both pure antimatter systems (antihydrogen, $\overline{\mathrm{H}}$) [1,2] and mixed matter–antimatter systems (antiprotonic helium) [3] for fundamental studies of the laws of nature. Protonium (Pn) is also of interest, since precision spectroscopic measurements may allow determination of the so-called antiprotonic Rydberg constant and/or the $\bar{\mathrm{p}}/e^-$ mass ratio.

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Here we report a new method of Pn production achieved by means of a chemical reaction between p̄s and molecular hydrogen ions (H_2^+) in the ATHENA $\overline{H}$ apparatus [1,4]. In the central part of the ATHENA apparatus a nested penning trap, 2.5 cm in diameter and ~10 cm in length immersed in an axial magnetic field of 3 T, allowed the confinement of positrons (e^+) and p̄. The residual pressure of $\sim10^{-12}$ Torr, in the 15 K cryogenic environment of the trap, was due to hydrogen and helium gases. Around 10^4 p̄ was injected into the positron plasma (a spheroidal cloud of $\sim3.5\times10^7 e^+$) for $\overline{H}$ production. A position sensitive detector [4,5] surrounded the trap and monitored the p̄ annihilations through the reconstruction of the tracks of the emitted charged pions.

During so-called "cold mixing" (CM), when the (e^+) cloud was in thermal equilibrium with the trap ambient at 15 K, most of the events were due to $\overline{H}$ annihilations [1,6]. Otherwise during "hot mixing" (HM), when the (e^+) were heated to a temperature T_e of 8000 K [6,7], $\overline{H}$ formation was suppressed and the p̄ annihilations were mainly due to collisions with trapped positive ions. It is this latter effect, which occurs also in CM, that is presented here.

Fig. 1 shows r–z scatter plots for annihilation vertices taken under HM and CM conditions. Here the axial coordinates, z, of the events are plotted versus their radial positions, r (i.e. the distance from the trap axis). The data are broadened by the uncertainties in the vertex determination (around 1.8 mm in the z-direction and 3.5 mm in the transverse dimensions). There are striking differences between the two r–z plots. Besides the $\overline{H}$ annihilations on the trap wall centred around $r = 1.25$ cm (CM only), there are events localized at smaller radii which dominate in HM (Fig. 1(a)), but which are also evident in CM (Fig. 1(b)) in the central z region.

In order to determine the characteristics of the annihilating systems, the multiplicity of the charged pions coming from the annihilations has been analyzed. In Table 1 we report for different data samples the ratios R_{23} of the number of the reconstructed annihilation vertices having two tracks to those with three tracks. From Table 1, the R_{23} values for annihilation on the trap wall for all the samples agree, within uncertainties, but differ from those for the trap centre by four standard deviations, indicating different annihilating systems. It is likely that the trap centre events are due to p̄p annihilation, since the Monte Carlo result obtained for this system agrees well with the experiment.

Different hypotheses about the nature of the annihilating systems have been considered. A careful analysis (see [8] for details) excludes the possibility that the near-axis events could be $\overline{H}$ annihilations or p̄ annihilations in-flight on the residual gases or on trapped ions. Thus, only the following explanation survives: the near-axis events are due to the annihilation of protonium atoms formed when positive ions capture p̄ in the central part of the apparatus. On formation the neutral systems leave the centre of the penning trap and annihilate at a position which is dependent upon their velocities and lifetimes.

We have performed Monte Carlo simulations in order to check this hypothesis and to determine the physical quantities affecting the data. In Fig. 2, simulated events of Pn production and annihilation are shown (for clarity, the charged pions trajectories of only one Pn decay are depicted).

In order to fit the experimental data we have taken into account the dimensions ($r_P = 1$ mm and $z_P = 16$ mm) and the rotation frequency ($\omega = 300$ kHz) of the (e^+) cloud measured by means of the non-destructive technique described in [7,9]. The best fit to the experimental data has been obtained with the following assumptions:

- The Pn are formed on the surface of the (e^+) plasma ($r = r_P = 1$ mm with a Gaussian distribution along the z axis centred at the symmetry plane of the plasma with $\sigma = 2.5$ mm for CM and $\sigma = 10$ mm, but limited to the length of the (e^+) plasma, for HM). It should be noted that the HM data are not strongly dependent on the initial radial position of the Pn.
- The Pn velocity is given by the sum of the isotropic thermal velocity v_{th} given by a Maxwellian distribution and of the velocity v_{tang} induced by the (e^+) plasma rotation.

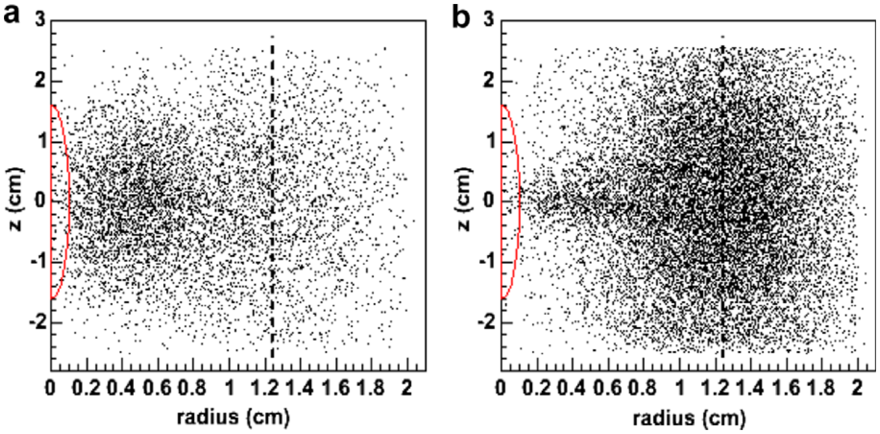

Fig. 1. r–z scatter plot of the annihilation vertices for (a) hot mixing; (b) cold mixing. The dashed line indicates the trap wall position; the semi-ellipse shows the section of the positron plasma.

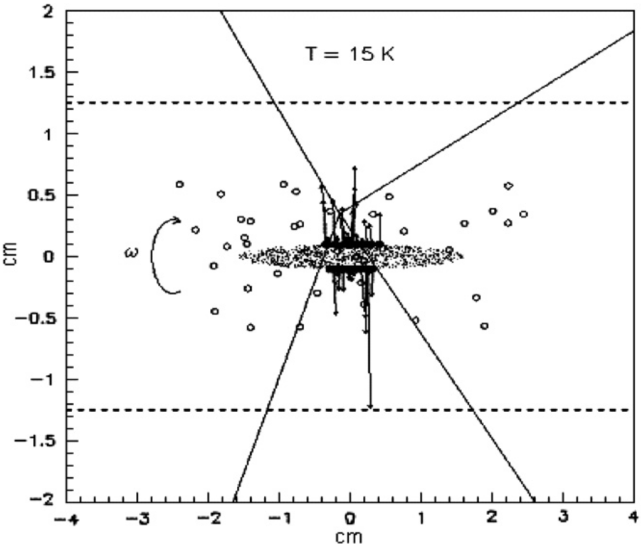

Fig. 2. Sketch of the simulated protonium production and decay in the ATHENA apparatus. The spheroid is the positron plasma, the black large points are the hydrogen ions, the empty large points are the antiprotons, the arrows are the displacement vectors of the protoniums from production to decay, the continuous lines are the charged pion trajectories produced by the protonium decay and the dashed lines are the trap wall.

The corresponding mean radial kinetic energy of Pn is about 40 meV for CM (dominated by v_{tang}) and 700 meV for HM (dominated by v_{th}).

- The Pn decay exponentially: the best fit corresponds to a mean lifetime of (1.1 ± 0.1) μs.

The results of the simulations and the experimental data are plotted in Fig. 3 for the HM case. The agreement is good with a reduced χ^2 of 1.48. The agreement of the simulated data and experimental results to is also good in the CM case where we have used the same lifetime as derived from the best fit to the HM data.

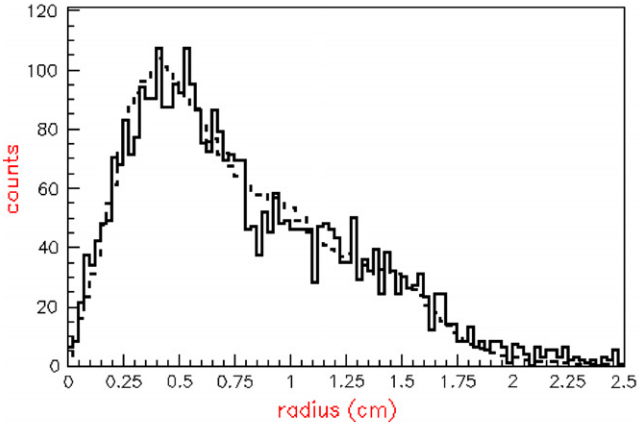

Fig. 3. Experimental radial distribution (continuous line) of annihilation vertices for HM (−1.5 cm < z < 1.5 cm) with a Monte Carlo simulation (dashed line, $T_e = 8000$ K, $v_{\text{th}} = 5600\ \text{m s}^{-1}$, generation on the surface of a spheroid with $z_p = 16$ mm and $r_p = 1$ mm rotating with a frequency of 300 kHz, i.e. $v_{\text{tang}} = 2000\ \text{m s}^{-1}$); see text for details.

It is notable that the simulations show that the Pn velocities are determined predominantly by the thermal and plasma environment and any attempt to reproduce the CM and HM data assuming Pn recoil energies of the order of 1 eV or higher fails (see Table 1).

Therefore, also taking in account that, in a dedicated measurement of the charge following emptying of our trap we have detected the presence of (H_2^+), we can infer that the Pn production mechanism is

$$\bar{\text{p}} + \text{H}_2^+ \rightarrow \text{Pn}(n, l) + \text{H}$$

The presence of H_2^+ in the trap could be a consequence of the collisions with H_2 residual gas by (e^+) during the (e^+) transfer procedure [10] or by $\bar{\text{p}}$ during $\bar{\text{p}}$ loading (see also [11]). We estimate the presence of about 10^4–10^5 ions under typical ambient conditions. This value, together with the number of around 100 Pn annihilations observed every 60 s $\bar{\text{p}}$ injection cycle for CM and HM, gives a cross section consistent with recent calculations [12].

From the kinematics of the $\bar{\text{p}}$–H_2^+ collision it is straightforward to calculate that the principal quantum number n of the emitted low-recoil Pn is around $n = 68$ with the emitted H atom in the ground state, in disagreement with [12] which predicts a production of Pn with substantial recoil at $n = 34$.

Since in a near-vacuum condition the Pn is expected to deexcite only by slow radiative transitions, the measured lifetime of 1.1 μs indicates that the Pn production occurs at low angular momentum ($L < 10$), see Fig. 4. This can

Table 1
Experimental and Monte Carlo results for the number of charged pion tracks due to antiproton annihilations

Data set	Ratio R_{23} on wall	Ratio R_{23} at centre
Cold mixing	1.35 ± 0.01	1.22 ± 0.04
Hot mixing	1.38 ± 0.10	1.17 ± 0.04
$\bar{\text{p}}$s only	1.40 ± 0.03	–
Monte Carlo $\bar{\text{p}}$p	1.19 ± 0.01	1.19 ± 0.01

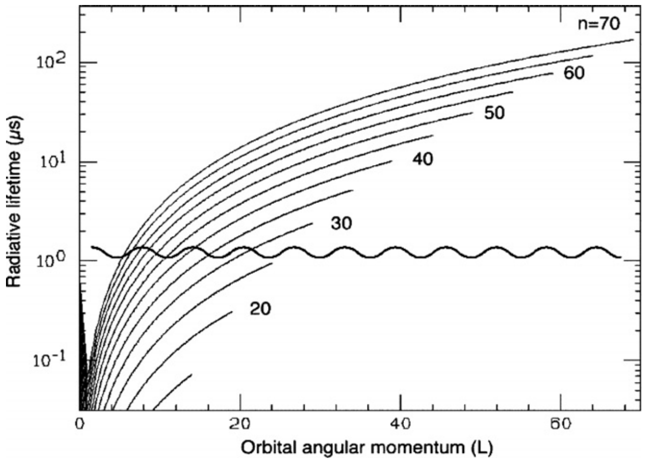

Fig. 4. Radiative level lifetimes of protonium for different principal quantum numbers versus orbital angular momentum from [13].

be explained if we consider that the (H_2^+) is polarised by the slow $\bar{p}$, resulting in collinear collision.

In conclusion, ATHENA has produced metastable Pn with sub-eV kinetic energies. By exploiting the capability of accumulating 10^8 H_2^+ ions in tens of seconds and storing $\sim 5 \times 10^6 \bar{p}$ in some minutes [14,15], this result shows that detailed spectroscopic measurements on Pn can be undertaken at low energy antiproton facilities, such as the AD at CERN or the future FLAIR at GSI.

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