Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Physics A 752 (2005) 97c–100c
NUCLEAR PHYSICS A

Antihydrogen production mechanisms in ATHENA

G. Bonomi[a], M. Amoretti[b], P. D. Bowe[c], C. Canali[b,d], C. Carraro[b,d], C. L. Cesar[e], M. Charlton[f], M. Doser[a], A. Fontana[g,h], M. C. Fujiwara[i,j], R. Funakoshi[i], P. Genova[g,h], J. S. Hangst[c], R. S. Hayano[i], L. V. Jørgensen[f], A. Kellerbauer[a], V. Lagomarsino[b,d], R. Landua[a], E. Lodi Rizzini[h,k], M. Macrí[b], N. Madsen[c], G. Manuzio[b,d], P. Montagna[g,h], D. Mitchard[f], A. Rotondi[g,h], G. Testera[b,d], A. Variola[d], L. Venturelli[h,k], Y. Yamazaki[j], D. P. van der Werf[f], N. Zurlo[h,k]

[a]PH Department, CERN, 1211 Geneva 23, Switzerland

[b]Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy

[c]Department of Physics and Astronomy, University of Aarhus, 8000 Aarhus C, Denmark

[d]Dipartimento di Fisica, Università di Genova, 16146 Genova, Italy

[e]Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, Brazil

[f]Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK

[g]Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy

[h]Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy

[i]Department of Physics, University of Tokyo, Tokyo 113-0033, Japan

[j]Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan

[k]Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali, Università di Brescia, 25123 Brescia, Italy

Production of cold antihydrogen in electromagnetic traps by mixing of antiprotons and positrons has been previously reported [1–4]. The study of the dependence of the antihydrogen production upon the positron plasma density and temperature is an important tool to distinguish between the possible processes for the formation of antiatoms. In this article results concerning the temperature dependence will be presented, along with a preliminary analysis of the density dependence.

1. Introduction

The main physics goal of obtaining a sample of trapped and cold antihydrogen ($\bar{\mathrm{H}}$) atoms is to study, with spectroscopic methods, their atomic structure and to compare it with that of hydrogen. In this way a direct test of CPT invariance may be performed. The precision of such measurements depends on many parameters, but a relative pre-

0375-9474/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nuclphysa.2005.02.046

cision of 10^{-18} could, in principle, be achieved. Another possible experiment utilising a neutral antimatter bound state sample is the measurement of the antimatter gravitational acceleration on earth in order to test the Weak Equivalence Principle.

On the way to producing, trapping and storing antihydrogen for a sufficient time to allow spectroscopic measurements, first ATHENA [1] and then ATRAP [3] reported in 2002 the creation of samples of cold antihydrogen by mixing antiprotons ($\bar{p}$s) and positrons (e^+s) at low temperature in a nested Penning trap [5].

In the ATHENA experimental conditions it is anticipated that two main processes are responsible for $\bar{\mathrm{H}}$ formation: *radiative combination* ($e^+ + \bar{p} \rightarrow \bar{\mathrm{H}} + \gamma$) and *three-body combination* ($e^+ + e^+ + \bar{p} \rightarrow \bar{\mathrm{H}} + e^+$). In both cases the excess energy is carried away by a third body, being a photon in the first process and a positron in the second one. For further discussion about the two processes refer to [6–8] and references therein. The two mechanisms lead to different quantum state populations of the antiatoms, and have different dependencies on the positron plasma density and temperature (n and $T^{-0.63}$ for the radiative [8], n^2 and $T^{-9/2}$ [5,9] for the three-body). Important insights into the formation mechanism and state distribution can therefore be obtained by studying the temperature and density dependence of the production of antihydrogen. In a previous publication we reported the temperature dependence [10], in which we measured for the first time the $\bar{\mathrm{H}}$ production behavior as a function of the positron plasma temperature from 15 K up to more than 3000 K. In this article we summarize the results of these measurements and report a preliminary analysis of the density dependence.

2. Antihydrogen production

The ATHENA collaboration started to collect data at CERN in 2000 and produced a total of about 2 million antihydrogen atoms during runs in 2002 and 2003. Briefly, the experimental apparatus consists of an antiproton capture trap, a positron accumulator and a mixing trap in which the two species of particles are brought together in a nested Penning trap configuration (see fig.1), an arrangement that allows simultaneous trapping of oppositely charged particles [5]. The mixing trap is surrounded by a detector [11] able to reconstruct the decay products of $\bar{p}$ and e^+ annihilations. For details concerning the experimental setup refer to [12].

Both the ingredients necessary for making $\bar{\mathrm{H}}$, that is $\bar{p}$s and e^+s, are separately trapped, cooled and accumulated prior to mixing in the nested trap. The antiprotons are delivered by CERN's Antiproton Decelerator (AD) [13] and the positrons emitted from a ^{22}Na radioactive source. The standard mixing cycle procedure in ATHENA is the following: the central part of the nested trap is filled with positrons (from 30 to 70 million); the positrons cool down with a time constant $\tau \simeq 0.5$ sec to the trap temperature by emission of synchrotron radiation [14]; about 10000 antiprotons are then injected and the two species of particles are allowed to interact for a time interval that can vary from 1 to 3 minutes. At the beginning the antiprotons, passing through the positrons many times, are cooled and after a few tens of ms antihydrogen formation begins [10,15]. At the end of the mixing cycle we empty the nested trap, counting both the number of remaining positrons and antiprotons, and then the process is restarted. In the mixing region the necessary experimental conditions for making $\bar{\mathrm{H}}$, such as cryogenic temperature ($\sim$15 K), very low pressure (<10^{-12} mbar) and high magnetic field (3 T) for radial confinement of charged particles, are provided by our experimental apparatus.

When formed, neutral $\bar{\mathrm{H}}$ atoms escape the confinement region and annihilate on the trap electrodes producing a signal in the surrounding detector that triggers the detector readout with an efficiency of 90 ± 10 %. The annihilation byproducts (charged πs from the $\bar{p}$, γs from the e^+) are then detected. For details on the antihydrogen signal selection and detection refer to [1,2,10]. It is important here to recall that 65 ± 5 % (2002) and 74 ± 5% (2003) of the triggers generated in our detector were due to antihydrogen annihilations. The remainder was due to annihilations of antiprotons on residual gas or ions in the center of the trap (refer to [1,2,10] for more details about background subtraction). As antihydrogen production rate proxy we can thus use the trigger rate (see [2,10]).

Just before the mixing cycle starts, we are able, using a non-destructive method [16,17], to measure some positron plasma characteristics such as density n_{e^+} and aspect ratio $\alpha = \frac{l_{e+}}{r_{e^+}}$, where l_{e^+} and r_{e^+} are the plasma semi-length and the radius . Also, we are able to induce heating at the positron plasma and measure its temperature increase [16,17]. This method allowed a measurement of the $\bar{\mathrm{H}}$ production as a function of the positron plasma temperature, assuming a base temperature of 15 K (see fig. 2).

During 2003 runs the positron plasma density varied almost an order of magnitude between 3×10^8 and 1.6×10^9 cm^{-3}. Thus, we could, in principle, study the density dependence of $\bar{\mathrm{H}}$ formation. However, the radius of the $\bar{p}$ cloud was unknown but was larger than that characteristic of the e^+ plasmas. In order to analyze the concomitant overlap problem, consider the antiproton to have a radial density $\sigma_{\bar{p}}$. The initial antihydrogen production rate is obviously proportional to the total number of antiprotons that interact with the positron plasma. This can be calculated by integrating $\sigma_{\bar{p}}$, that is $N_{\bar{p}} = \int_o^{r_{e^+}} \sigma_{\bar{p}}\, \pi r \ \mathrm{d}r$. If we parametrize the antiproton radial density as a power of the radius, $\sigma_{\bar{p}} \propto r^m$, then $N_{\bar{p}} \propto r_{e^+}^{m+2}$. In order to study the antihydrogen density dependence we must correct for this factor and divide the number of triggers by $r_{e^+}^{m+2}$ before plotting them as a function of the positron density. Unfortunately, at the time of writing, the antiproton radial density has not been extracted, however work is ongoing and progress is expected soon.

3. Conclusions

The temperature dependence of antihydrogen production has been studied for the first time and an analysis is underway which promises to unravel the density dependence.

Concerning the temperature dependence (see fig. 2), a clear decrease in antihydrogen production with the positron plasma temperature has been observed, but a simple power-law scaling does not fit the data. The leveling-off at low temperature, below ~ 100 K, and the behavior at high temperatures are not consistent with the expected three-body temperature dependence ($T^{-9/2}$). The presence of $\bar{\mathrm{H}}$ production at room temperature, and the behavior at high temperature, suggest that the radiative mechanism cannot be completely excluded in ATHENA, leading to anti-atomic states that are more tightly bound than those observable using field ionization techniques. Nevertheless the radiative $\bar{\mathrm{H}}$ production rate prediction is at least an order of magnitude lower than our peak production rate of more than 400 Hz [10]. A better understanding of the complex inter-

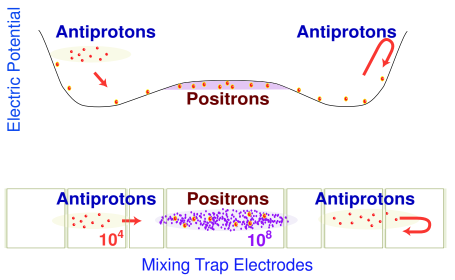

Figure 1. Schematic illustration of the nested trap region where positrons and antiprotons are mixed.

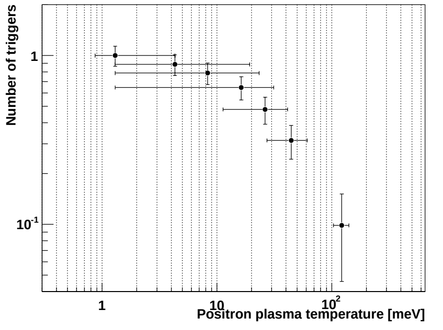

Figure 2. Temperature dependence of $\bar{\text{H}}$ production using the number of triggers. See [10] for more details.

play of production and ionization processes (for three-body), the effects of finite transit time of antiprotons through positrons, the effects of magnetic field on $\bar{\text{H}}$ production, and the role of "guiding center atoms" [9] is desirable to further our understanding of the mechanism(s) of antihydrogen formation.

REFERENCES

1. M. Amoretti *et al.*, Nature **419** (2002) 456.
2. M. Amoretti *et al.*, Phys. Lett. B **578** (2004) 23.
3. G. Gabrielse *et al.*, Phys. Rev. Lett. **89** (2002) 213401.
4. G. Gabrielse *et al.*, Phys. Rev. Lett. **89** (2002) 233401.
5. G. Gabrielse *et al.*, Phys. Lett. A **129** (1988) 38.
6. M. H. Holzscheiter and M. Charlton, Rep. Prog. Phys. **62** (1999) 1.
7. A. Müller and A. Wolf, Hyp. Int. **109** (1997) 233.
8. J. Stevefelt, J. Boulmer and J-F. Delpech, Phys. Rev. A **12** (1975) 1246.
9. M. E. Glinsky and T. M. O'Neil, Phys. Fluids B **3** (1991) 1279.
10. M. Amoretti *et al.*, Phys. Lett. B **583** (2004) 59.
11. C. Regenfus, Nucl. Instr. and Meth. A **501** (2003) 65.
12. M. Amoretti *et al.*, Nucl. Instr. and Meth. A **518** (2004) 679.
13. F. Y. Hémery and S. Maury, Nucl. Phys. A **655** (1999) 344c.
14. T. M. O'Neil, Phys. Fluids **23** (1980) 725.
15. M. Amoretti *et al.*, Phys. Lett. B **590** (2004) 133.
16. M. Amoretti *et al.*, Phys. Rev. Lett. **91** (2003) 055001.
17. M. Amoretti *et al.*, Phys. Plasmas **10** (2003) 3056.