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Formation of Low-Energy Antihydrogen

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Antihydrogen atoms, produced near rest, trapped in a magnetic well, and cooled to the lowest possible temperature (kinetic energy) could provide an extremely powerful tool for the search of violations of CPT and Lorentz invariance. We describe our plans to trap antiprotons and positrons in a combined Penning trap and to form a significant number of cold antihydrogen atoms for comparative precision spectroscopy of hydrogen and antihydrogen.

1. Introduction

CPT invariance is a fundamental property of quantum field theories in flat space-time, which results from the basic requirements of locality, Lorentz invariance and unitarity [1–4]. Principal consequences include the predictions that particles and their antiparticles have equal masses and lifetimes, and equal and opposite electric charges and magnetic moments. It also follows that the fine structure, hyperfine structure, and Lamb shifts of matter and antimatter bound systems should be identical.

A number of experiments have tested these predictions with impressive accuracy [5], e.g. with a precision of 10^{-12} for the difference between the module of the magnetic moment of the positron and the electron [6] and of 10^{-9} for the difference between the proton and antiproton charge-to-mass ratio [7]. The most stringent CPT test to date comes from a mass comparison of neutral kaon and antikaon, where an accuracy of 10^{-18} has been reached, albeit in a theoretically dependent manner.

Recent years have seen a steady increase in discussions of possible mechanism for, and implications of, CPT violation [8–10]. Specifically, a model based on an extension of the Standard Model (SM) and Quantum-Electrodynamics (QED) has been formulated and used to quantitatively analyze specific experiments for their sensitivity to CPT and Lorentz violations [11]. In the framework of this theoretical model existing and proposed experiments have been studied and new, more meaningful figure-of-merits have been established for measurements of g-2 for electrons and positrons [12], for comparisons of the charge-to-mass ratios of antiprotons, protons, and negative hydrogen ions, as well as for measuring the ratio of the magnetic moments of protons and antiprotons [13]. Similar work analyzing the sensitivity of specific spectroscopic measurements in hydrogen and antihydrogen to CPT and Lorentz violation show that the highest sensitivity may be

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achieved in studies of the hyperfine interaction in antihydrogen [14].

The formation of antihydrogen has been demonstrated to date in flight by two experiments [15,16]. Antihydrogen was formed by collisions between high energy antiprotons and a gas jet, creating electron-positron pairs. In kinematic favorable cases the antiproton could capture a positron and continue its flight path as a neutral antihydrogen atom. While this was sufficient to identify the formed antihydrogen, the extremely low production rate and the relativistic energy of the particles prohibited any measurements at a level of accuracy necessary for meaningful tests of CPT and Lorentz invariance. Such precision can only be reached by capturing antihydrogen in a magnetic trap and cooling it to the lowest possible temperatures.

2. Experimental overview

In order to form antihydrogen atoms at rest one starts by storing the charged constituents in electromagnetic field configurations known as Penning traps and cooling them by coupling the particles motion to the ambient temperature of the (cryogenic) environment. Antihydrogen atoms then formed by overlapping the two oppositely charged particle plasmas will carry the kinetic energy of the heavier particle, the antiproton, and therefore will be "cold" as well.

The technique of capturing antiprotons into traps and cooling them to milli-eV energies has been developed at LEAR over the last 10 years [7,17]. To reduce the kinetic energy of the incoming beam from 5.9 MeV to several tens of keV,where electromagnetic trapping of particles has been demonstrated, energy loss in thin foils [18] is being used. To capture and confine the antiprotons once the energy has been reduced to $\leq$ 30 keV, we employ a modified Penning trap [19]. The trap structure typically consists of seven electrodes: the entrance foil, a central region comprising five cylinders (two endcaps, two compensation electrodes, and the central ring), and a cylindrical high voltage exit electrode. The trap system is situated in the cryogenic bore of a superconducting solenoidal magnetic field of 3 to 6 Tesla for radial confinement, while the axial confinement is given by the electrostatic potentials applied to the trap electrodes.

Electron cooling is used to reduce the initial antiproton energy of several keV to values below 1 meV. For this purpose, a dense electron cloud is preloaded into the central region of the trap. These electrons cool to equilibrium with their cryogenic environment via synchrotron radiation with a time constant of $\leq$ 0.4 s at 3 Tesla. The antiprotons oscillate through the cold electron cloud and lose their energy via Coulomb collisions with a time constant of a few minutes and are collected in the central trap well. The efficiency observed for this process is better than 90%.

Our previous experiment at LEAR, PS200, has set the world record in collecting and cooling one million antiprotons from a single shot from LEAR [20] (see figure 1). It has also demonstrated that subsequent pulses can be "stacked" to increase the overall number of antiprotons in the trap.

Using this method we plan to accumulate 10^7 cold antiprotons from the Antiproton Decelerator (AD) [21] currently under construction at CERN.

For the accumulation of positrons we will use a system based upon the positron accumulator developed at the University of California in San Diego [22,23]. The instrument is

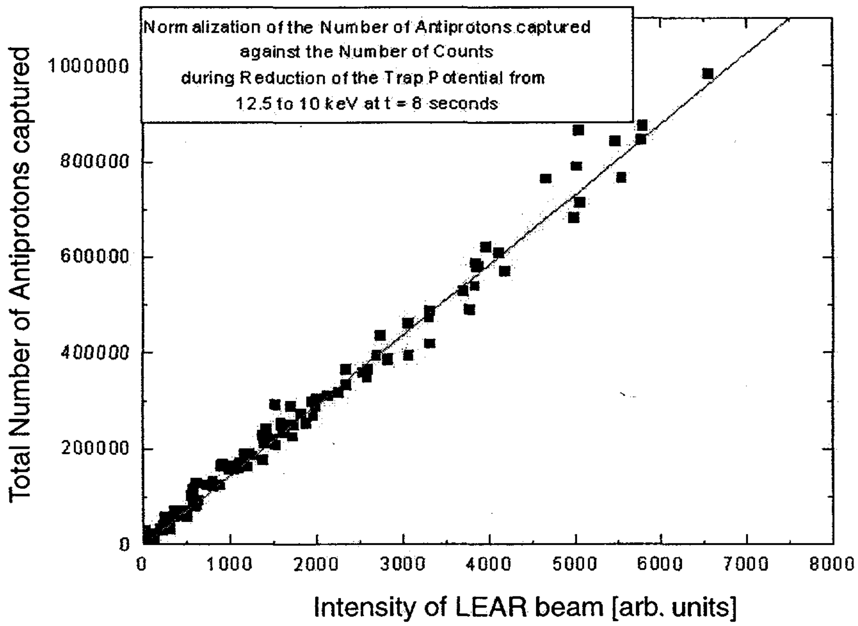

Figure 1. *Accumulation of antiprotons in the PS200 trap for different LEAR beam intensities.*

a so-called Penning-Malmberg trap in which low energy positrons are confined axially by a series of electrical potentials and radially by an axial magnetic field of typically 0.2 T.

Slow positrons enter the electrode arrangement into the front region of the trap which contains N_2 gas at a pressure of around 10^{-3} torr ($\sim 10^{-1}$ Pa). The gas is introduced at the center of the first electrode, and differential pumping between this region and the remainder of the trap gives rise to a pressure gradient in axial direction.

Positrons pass through the different pressure regions before being reflected by the electrical potential in the last region, after which they return towards the entrance of the trap. During the transit there is a reasonable chance, around 30%, of a positron losing energy by electronic excitation of the N_2. Such positrons are then trapped and oscillate back and forth until they eventually lose further energy by exciting vibrational and rotational transitions of the N_2 molecule, thereby falling deeper and deeper into the electrostatic well and towards the low pressure region of the apparatus.

In this manner, positrons can be continuously accumulated with a time dependence $N(t) = R\tau[1 - \exp(-t/\tau)]$, where R is the trapping rate and τ is the lifetime in the trap. As shown in figure 2, this instrument has accumulated around 10^8 positrons in times of the order of 100 seconds. The positron lifetime in the system is governed largely by annihilation on the N_2 buffer gas. Under steady state conditions the lifetime is around 60 s, but increases

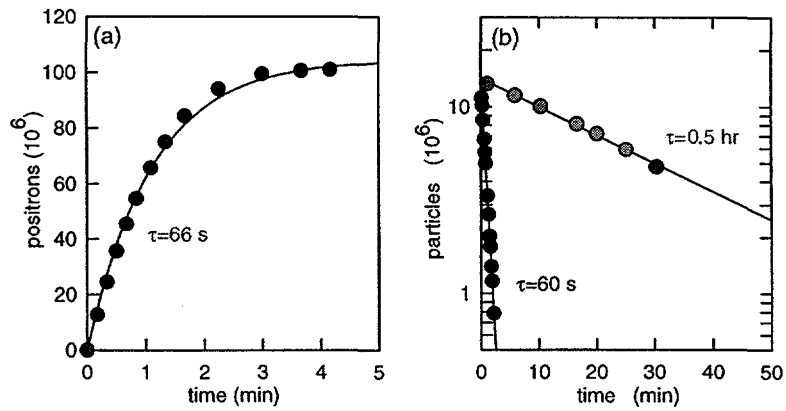

Figure 2. *(a) Accumulation and (b) lifetime of positrons in the final trapping stage.*

to 30 minutes if the N_2 gas is pumped out at the end of the accumulation period.

One of the major challenges in the formation of antihydrogen will consist of bringing the oppositely charged antiprotons and positrons in close contact for a time sufficiently long to allow the recombination process to take place. For this we will use a nested Penning trap [24] which consists of a sequence of axial electrostatic wells in a common magnetic field. These wells are arranged in such a way that particles of opposite charge are stored in separate locations in close proximity. Mixture of the plasmas can be achieved by adjusting the potential wells or by heating the particles in one well so they can leak over the barrier into an adjacent well. Latter method has been used to generate ultra-low energy beams from Penning traps [25] and appears to be a promising scheme to mix dense antiproton and positron clouds at low relative velocity.

3. Antihydrogen formation

To form a bound state of antiproton and positron starting from free particles, excess energy and momentum has to be carried away by a third particle. Various schemes for this have been proposed and discussed in the literature in some detail [29–35], with the first mentioning of the possible production of antihydrogen in traps by Dehmelt and co-workers [36]. The simplest process is spontaneous radiative recombination which can be enhanced by laser stimulation:

$$e^+ + \overline{p} + nh\nu \Rightarrow \overline{H} + (n-1)h\nu \;.([29--31]). \tag{1}$$

An entirely different approach is based on three-body collisions: [24,32–35]:

$$e^+ + e^+ + \overline{p} \Rightarrow \overline{H} + e^+ \;, \tag{2}$$

The most critical issues to be considered in the analysis of a specific reaction for the purpose of providing trapped antihydrogen atoms are the total recombination rate and the distribution of states in which the antihydrogen atoms are produced.

The cross-section for spontaneous radiative recombination [37] is related by time-reversal invariance to photo-ionization, and depends only on the kinetic energy E of the electron in the center-of-mass (c.m.) system of the proton, and the capture level n:

$$\sigma_{SRR}(n,E) = 2.1 \cdot 10^{-22} cm^2 \frac{1}{nx(1+n^2x)} \quad x = E/E_0, \quad E_0 = 13.6eV, \quad E = \frac{1}{2}mv^2 \;. \quad (3)$$

This cross-section decreases with high n and predominantly low-lying n states are populated ($\approx$ 60% of the atoms are produced in states n $\leq$ 10). The total cross-section is obtained by summing over all n up to a "cut-off" level n_{cut}, which is reached when antihydrogen atoms are ionized in collisions with neighboring atoms or by external electric fields. For example, a temperature of the antihydrogen atoms of 4 K (or an ambient electric field of 1 V/cm) would lead to a cut-off at $n_{cut} \sim 200$. For a center-of-mass energy of $E_{c.m.} \sim 0.1$ meV we obtain an order of magnitude estimate for the reaction rate $\alpha(v_r) = \langle \sigma(v) v \rangle = 0.9 \cdot 10^{-10}$ This value agrees within a factor 2 or better with more elaborate calculations [38] and with experimental results from storage ring experiments [39]. With the parameters for the charged plasmas $N_e = 10^8$, $N_p = 10^7$ anticipated for the ATHENA apparatus, we obtain an upper limit for the spontaneous recombination rate R = 90.000 atoms/sec .

Three-body recombination (TBR) plays a role predominantly at high positron densities and very low temperatures. The rate $\alpha_{TBR}(n)$ as a function of the capture level n has been calculated [40] by considering the time-reversed process, i.e. electron-impact ionization of hydrogen, which is well known, yielding:

$$\alpha_{TBR}(n) = 1.96 \cdot 10^{-29} cm^6 s^{-1} n_e \left(\frac{1}{kT/eV} \right) n^6 \quad (4)$$

The steep dependence on the principal quantum number n indicates that mostly very high Rydberg states close to the "cut-off" level $n^* \sim \sqrt{R/2kT}$, $R = 13.6$ eV, are populated. Summing up all contributions from n=1 to n^*, the total three-body recombination rate for a Maxwellian positron velocity distribution of temperature T becomes:

$$\alpha_{TBR}(n^*) = 2.7 \cdot 10^{-27} cm^6 s^{-1} n_e \left(\frac{1}{kT/eV} \right)^{4.5} \quad (5)$$

which highlights the strong temperature dependence, in excellent agreement with previously quoted results [41].

4. Summary

We have described the plans of the ATHENA collaboration to form ultra-low energy antihydrogen atoms for precision spectroscopy. While all individual steps have been demonstrated in separate experiments, combining them in a single experiment is posing a formidable challenge. But once the formation and capture of antihydrogen atoms has been achieved a powerful new probe for fundamental physics will be available, undoubtedly leading to interesting physics results.

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