

Efficient Accumulation of Antiprotons and Positrons, Production of Slow Mono-Energetic Beams, and Their Applications

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Abstract. Recent progress of ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) project, particularly the antiproton trapping and slow antiproton production, is discussed. An RFQD (Radio Frequency Quadrupole Decelerator) installed in the ASACUSA beam line has an excellent deceleration efficiency of 25% providing 10-130keV antiprotons, which improves the final accumulation efficiency at least one and half orders of magnitude. The decelerated antiprotons are then injected in a large volume multiring trap, stored, and electron-cooled. About 1 million antiprotons are successfully accumulated per one AD shot and 10-500eV antiprotons are extracted as a mono-energetic beam. A UHV compatible positron accumulation is newly developed combining electron plasma and an ion cloud, which yields an accumulation rate as high as $400e^+/s/mCi$, two and a half orders of magnitude higher than other UHV compatible schemes. A new scheme to synthesize a spin-polarized antihydrogen beam is also discussed, which will play a vital role in determining the magnetic moment of antiproton with high precision.

Introduction

Interaction of charged particles with atoms, molecules and solids has fundamental importance not only in basic science but also in various fields of applied sciences. We have been developing various kinds of slow and ultra-slow charged particles like antiprotons, positrons, highly charged ions, and short-lived RI ions considering that new and unknown fields emerge. In the present report, antiproton and positron are discussed together with their reaction product, antihydrogen, a key material for various CPT tests.

The kinetic energies of antiparticles when they are produced are similar to their rest mass energy distributed over a large phase space volume. Therefore, deceleration and trapping become practically feasible only after compression of the volume (often called “cooling”), the procedure of which is common to all the particles in question here. Further, the compression should be done avoiding annihilation with matter. Because of these constraints, all the procedures like cooling, deceleration and accumulation should be done in (ultra high) vacuum. The Antiproton Decelerator (AD) at CERN [1] devoted primarily to atomic physics experiments, cools and decelerates 3.5GeV/c antiprotons down to 100MeV/c (5.3MeV/u) and supplying antiprotons of 2×10^7 \bar{p} /pulse every 100sec. With the advent of AD, research with slow antiproton beam can now be done much more readily [2-6]. ASACUSA collaboration (Atomic Spectroscopy And Collisions Using Slow Antiprotons) was formed aiming at studying atomic physics aspects with antiprotons including the nature of antiprotonic helium [7], antiprotonic atom and antihydrogen atom formation processes [8]. One of the most important tools of ASACUSA is the RFQD (Radio Frequency Quadrupole Decelerator) [9], an energy variable decelerator with high deceleration efficiency. Slow antiprotons from the RFQD have readily been used for \bar{p} He laser spectroscopy under low pressure He target as well as for trapping and

extracting ultra-slow antiprotons. Combined with a multiring trap (MRT) [10], several millions of antiprotons are successfully stored and cooled [8,11]. These developments are expected to accelerate not only the elucidation of the process by which antiprotonic atoms are formed, but also the synthesis and study of antihydrogen atoms, and spectroscopic study of the antiprotonic atoms.

Recently, two groups working at AD have succeeded in synthesizing antihydrogen atoms ($\bar{\text{H}}$) [12,13] employing a so-called nested trap scheme, one of the most important milestones toward high precision spectroscopy of antihydrogen. Because the experimental resolution is governed by the interaction time, trapping antihydrogen by laser cooling or by non-uniform magnetic field is the unavoidable next step. In the case of the nested trap, however, a uniform magnetic field is used, which is in conflict with the magnetic trap. Several alternative confining-field configurations have been proposed to avoid these problems [14]. We have recently proposed a new scheme, which is discussed in the following section.

\bar{p} Accumulation

Antiprotons are produced in proton-nucleon collisions, e.g., $p + p \rightarrow \bar{p} + p + p + p$. In the case of AD, 3.5GeV/c antiprotons produced with 26GeV/c protons are accumulated. After several steps of stochastic cooling, deceleration, and electron cooling, 100MeV/c (5.3MeV/u) antiprotons are prepared, which are eventually extracted as a pulsed beam of 90ns in width containing 2×10^7 antiprotons every ~ 100 sec. Usually, a simple degrader foil technique is applied to this 5MeV beam to prepare antiprotons around 10keV and lower for trapping in a Penning-type trap, where the trapping efficiency cannot at all be great. In order to overcome this difficulty, the RFQD (Radio Frequency Quadrupole Decelerator) [9], an energy variable decelerator (10-130keV), has been installed in the ASACUSA beam line. The deceleration efficiency has been found to be $\sim 25\%$, i.e., ~ 5 million antiprotons are supplied from the RFQD per one AD shot.

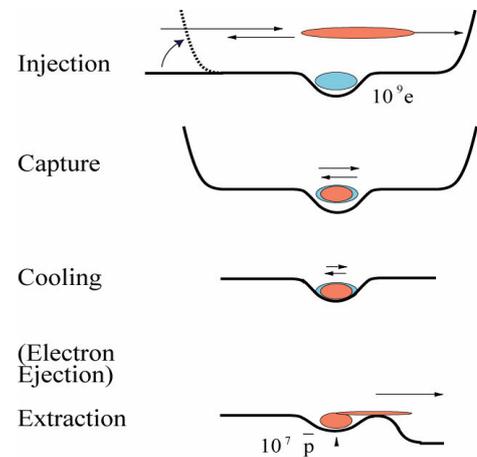


Fig.1: A schematic drawing of the antiproton trapping and cooling scheme.

Antiprotons so decelerated are injected in an MRT (MultiRing Trap) via two thin foils ($\sim 90 \mu\text{g}/\text{cm}^2$ each), which “decelerate” antiprotons with energies less than 10keV. As shown in fig.1, decelerated antiprotons are guided in the MRT and reflected by a downstream end electrode of the MRT, which is biased -10kV . Before the reflected antiprotons reach an upstream end electrode, which is grounded when the decelerated antiprotons are guided in, is now biased at -10kV with a fast switch, thus antiprotons are confined in the MRT. Antiprotons are then cooled below eV with electrons preloaded at the center of the MRT, and eventually condensed together. At the moment, ~ 1 million antiprotons are stored per one AD shot, which is several tens times more efficient than the simple degrader foil scheme. By stacking antiprotons for several AD shots, several million antiprotons are accumulated, which is the largest number ever stored at rest.

A harmonic potential is formed around the antiproton and electron trapping area, which enables to stably store a large number of antiprotons [10], and, at the same time, to figure out the shape, density, and temperature of the electron plasma non-destructively by monitoring electrostatic eigenmodes of the plasma. For example, the frequency evolution of the (2,0) and (3,0) modes have been successfully observed when antiprotons are injected, revealing that the plasma temperature rises about 0.6eV within a few seconds, and then slowly back to the original temperature in a few tens seconds [11]. A similar feature has also been observed when energetic protons are cooled with electrons [15].

Cold antiprotons are then extracted as an ultra-slow mono-energetic beam of 10eV-500eV through a

specially designed beam line [16], which enables to transport antiprotons with high efficiency at the same time to make a differential pumping of more than 6 orders of magnitude.

Positron accumulation

The accumulation of a large number of positrons is, in addition to the \bar{p} accumulation, the key ingredient to synthesize antihydrogen. We have been developing an efficient and UHV (ultra high vacuum) compatible accumulation scheme. Once a large number of positrons are stored, a variety of applications will emerge, which includes low energy positron-atom/molecule collisions [17], plasma physics [18], positronium beam production [19], and positron cooling of highly charged ions [20]. Till now, only resistive cooling [21] and field ionization of positronium in high Rydberg states [22] are available as the UHV compatible schemes, where a ^{22}Na source is used. However, their efficiencies are relatively low (~ 2.8 , and $\sim 11 \text{ e}^+/\text{s/mCi}$, respectively). When UHV requirements are relaxed, a N_2 buffer gas method has been proved to be efficient [23], which accumulates more than $10^4 \text{ e}^+/\text{s/mCi}$ in vacuum of 10^{-4} Pa . A new scheme to be discussed here is UHV compatible and, at the same time, high efficiency, where a combination of high-density electron plasma and an ion cloud is used as the energy absorber instead of N_2 buffer gas.

Figure 2 schematically shows a layout of the experimental setup [24], which consists of an electron gun, a multi-ring trap (MRT), a movable W(100) re-moderator, a faraday cup, and a NaI γ -ray detector. The MRT and re-moderator are in a cryogenic UHV bore tube of a 5T superconducting solenoid. Slow positrons from a solid Ne moderator are transported into the MRT and injected on the re-moderator. Low energy positrons from the re-moderator are further decelerated through collisions with high-density electron plasma and an ion cloud in the MRT.

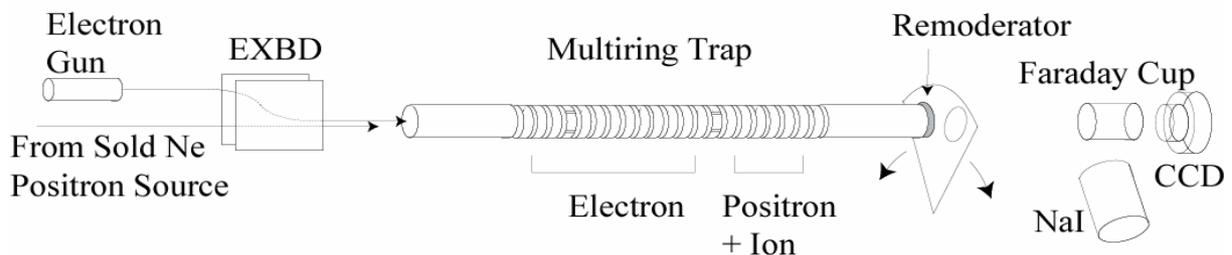


Fig.2: A schematic layout of the experimental setup for the UHV compatible positron accumulation system (see the text for details) [24]

The accumulation efficiency of positrons has been measured as a function of the number of electrons in the plasma, which increases monotonically, and the accumulation rate as high as $400\text{e}^+/\text{s/mCi}$ has been realized, which is more than 30 times higher than other UHV compatible schemes. It was found that the positron accumulation proceeds even without ions although the efficiency is reduced by a factor of 10 but no positrons are trapped if no electrons are in the trap, i.e., the primary mechanism of the accumulation is the energy loss of positrons in the electron plasma and then the momentum transfer collisions with ions in the positron trap as the second role. The observed trapping efficiency can be more or less reproduced when the stopping power of positrons in electron plasma is taken into account [25].

4. Polarized $\bar{\text{H}}$ beam with a cusp trap

A new scheme of cold antihydrogen synthesis is described in this section [26], which is realized by a recombination of a magnetic quadrupole (cusp) formed by a pair of superconducting solenoids and an electrostatic octupole formed by axially-symmetric five electrodes. Such a recombination trap is referred to as an MCEO (magnetic cusp and an electric octupole) trap hereafter. Slow positrons injected in the MCEO oscillate along the magnetic field line if the octupole electric field is applied after the positron injection [27].

In an inhomogeneous magnetic field \vec{B} , a positron with the orbital magnetic moment $\vec{\mu}_c$ is subject to the force $-|\vec{\mu}_c| \nabla |\vec{B}|$. In other words, positrons are in equilibrium along the magnetic field direction when the force due to their space charge balances with the sum of the octupole electric field and $-|\vec{\mu}_c| \nabla |\vec{B}|$, i.e., the number of positrons stored in the MCEO can exceed that of the electrostatic limit [28]. The maximum magnetic field of the MCEO under construction is $\sim 3.5\text{T}$ with the field gradient as strong as $\sim 30\text{T/m}$, i.e., positrons are cooled down via synchrotron radiation to the environmental temperature, which is $\sim 4\text{K}$. After positrons are stored and cooled, antiprotons are introduced along the MCEO axis. A couple of electrodes surrounding the MCEO are prepared to form additional electric fields outside of the MCEO, which prevents the antiprotons to escape from the MCEO area. Once thermalized, the antiprotons will condensate at the center of the MCEO together with the positrons. As a natural consequence, antihydrogen atoms are automatically synthesized even at very low temperature. Antihydrogen atoms formed at the center of the MCEO drift into a region with a finite magnetic field, where $\bar{\text{H}}$ atoms in low-field seeking (LS) states are decelerated and those in high-field seeking (HS) states are accelerated. When the kinetic energy of the LS atom is lower than the potential barrier of the cusp magnetic field ($\sim 0.2\text{meV}$ in the present case), such an atom is trapped in MCEO trap. When their energy is higher than the potential barrier, they overcome the barrier and eventually are focused like in the case of an electrostatic lens for charged particles. A numerical simulation predicts that LS atoms are effectively focused and the flux density is enhanced two and half orders of magnitude. On the other hand, HS atoms are defocused, i.e., a flux-enhance antihydrogen beam with high spin polarization is automatically prepared in the MCEO.

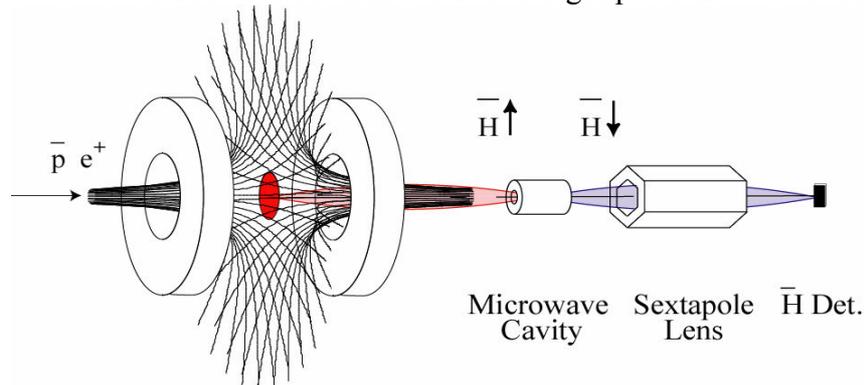


Fig.3: A schematic layout of the cusp trap and HFS measurements.

Figure 3 illustrates a possible configuration of the magnetic moment measurement system; an antihydrogen beam in LS states formed in the MCEO passes through the microwave cavity and spin flipped if the frequency matches with that of the HF transition, and enters the sextupole lens (magnet). If the spin-flip is induced, they are focused on the $\bar{\text{H}}$ detector. Considering the interaction time of antihydrogen with the microwave field is $\sim 1\text{ms}$ (a few hundreds m/s in velocity and the cavity size of a fraction of m, the order of the microwave wavelength), the antiproton magnetic moment can be determined with the precision of the order of ppm, which is 3 orders of magnitude improvement over the present value [26].

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