Antimatter Matters: Progress in Cold Antihydrogen Research

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Abstract. The purpose of cold antihydrogen research is briefly reviewed together with the latest developments of manipulating antihydrogen atoms. Two major progresses last year were the trapping of antihydrogen atoms in a magnetic bottle and synthesis of antihydrogen atoms in a cusp trap, where a spin-polarized antihydrogen beam can be extracted as an intensified beam. The magnetic bottle consists of an octupole coil and a pair of mirror coils, which improved the magnetic field uniformity near the axis, and so the stability of trapping antiprotons and positrons. Eventually, antihydrogen atoms were trapped for more than 1000s, which is ready to be testified with high precision laser spectroscopy. The cusp trap consists of a superconducting anti-Helmholtz coil and a stack of multiple ring electrodes. This success opens a new path to make a stringent test of the CPT symmetry via high precision microwave spectroscopy of ground-state hyperfine transitions of antihydrogen atoms.

1. Introduction
Synthesis of antihydrogen (H) atoms has been intensively studied in the last decades [1, 2]. The primary physics goal is to make stringent tests of the CPT symmetry either via high precision laser spectroscopy of 1S-2S transition [3, 4] or via high precision microwave spectroscopy of ground state hyperfine transitions [5, 6]. The hyperfine transitions are equally sensitive to the hadron as well as the lepton magnetic moments, which is compared with the 1S-2S transitions, where the lepton mass is the governing parameter in determining the transition energies. Recently, studies on the gravitational interaction of antimatter (H) and matter (the earth), the so-called weak-equivalence principle, are also proposed [7] or under preparation [8]. The cold antimatter research celebrated an important milestone in 2002, when successful syntheses of cold H atoms in a uniform magnetic field were demonstrated by two research groups [9, 10]. Both groups aim for 1S-2S high precision laser spectroscopy, and accordingly the next critical step is to prepare ultra-cold H atoms (< 1 K) in the low-field-seeking states and to trap them in the Ioffe-Pritchard trap or a variant of it having minimum B field configurations [11, 12].

Although antihydrogen atoms were successfully synthesized, they are not really under our control, and their syntheses were only confirmed by annihilation signals, i.e., it was a kind of archaeological approach confirming antihydrogen atoms existed sometime ago. Then the natural next step is to actively control antihydrogen atoms so that they can be used for real physics research. As is discussed later, there are two different approaches in progress. The most straightforward one is to trap antihydrogen atoms in a magnetic bottle so that they can be observed for macroscopic time, which in principle allows high precision measurements. Another scheme is to extract antihydrogen atoms into a field-free region as a focused beam, where the
intrinsic nature of antihydrogen is not disturbed by outer fields. Actually, near the end of last year (2010), two major achievements have been reported in this direction [13, 14], which are mainly described in this report. Regarding the trapping, the trapping time has later been extended by several orders of magnitude, as long as 1000s [15].

2. Purpose of Antimatter Research
Antihydrogen consisting of antiproton and positron is the opposite number of hydrogen consisting of proton and electron. The basic motivation to study cold antihydrogen is to realize high resolution spectroscopy and to make high precision comparison with hydrogen, which allows us to test the CPT (Charge conjugation, Parity inversion, Time reversal) symmetry, the most fundamental physics law. This is in itself quite important and interesting, but at the same time, it might also give critical information why the universe is filled with matter but not with antimatter. Further, non-neutral plasma physics plays an essential role in storing, manipulating, and mixing of antiprotons and positrons, and three body recombination processes in a strong magnetic field are an attractive and challenging subject of atomic collision physics.

Within the framework of the standard theory, which is formulated in a flat space-time, CPT is conserved. At the same time, if CPT is conserved, spectroscopic properties of antihydrogen should be exactly the same as those of hydrogen. Accordingly, if one succeeds to observe some difference even if tiny, this is the direct proof that CPT is not conserved irrespective of the reason why. It is noted in this sense that the test of the CPT symmetry does not need detailed theoretical support but experimental facts are the key. As already described, there are two major research directions, i.e., the measurements of 1S-2S transition and/or ground state hyperfine transitions. Till now, it is not clear which is better for the CPT symmetry test. Experimental findings tell everything, and at the moment, we are better to pursue both possibilities.

From a theoretical side, however, a so-called STME (Standard Model Extension) had been proposed and extended considerably by Kostelecky and his colleagues, where possible CPT violating interactions are artificially added trying to find what type of phenomena suit better to detect CPT violating effects. It was concluded that ground state hyperfine transitions are more sensitive to CPT violation [16].

In a gravitational field CPT can be violated\(^1\). In order to get an idea of the level of violation, a measure of violation due to gravitational field can be the Planck mass, \(m_{pl}\), which is given by \(\sqrt{\hbar c/G}\), where \(\hbar\) is the Planck constant divided by \(2\pi\), \(c\) the light speed, and \(G\) the gravitational constant. Actually, the Planck mass is huge, \(\sim 10^{19}\) GeV/\(c^2\). Although one may expect a strong CPT violation at this energy range, there is no way to reach this with present accelerator techniques, and will never be reached even in a far future. The history of modern physics is an education in our limitations, e.g., the light speed is the maximum one can reach, the uncertainty principle does not allow us to determine the position and the momentum of a particle simultaneously, etc. It would therefore make sense to reconsider our strategy for studying the fundamental law of nature. Instead of pushing to higher and higher energies, perhaps we should adopt a softer approach by exploring nature with extremely high sensitivities. We will call such an approach as “listen to the whisper of nature”.

Let’s try to find what level of whisper we need to handle. Assuming that the level of CPT violation is somewhat proportional to the mass range considered, it would be \(10^{-19}\) when hydrogen/antihydrogen is a target to be studied \((m_p/m_{pl}\), where \(m_p\) is the proton mass\). Or in the level of energy, it corresponds to \((m_p/m_{pl})m_p c^2 \sim 10^{-19}\) GeV. Although this is an extremely small quantity, it corresponds to 10kHz or so, which might be manageable.

Table 1 shows the difference between electron and positron, and between proton and

\(^1\) It is known that when CPT symmetry is broken, invariance with respect to the Lorentz transformation is also broken.
antiproton with respect to the mass, the charge, and the $g$-factor. The CPT symmetry with respect to mass and charge is well tested to the level of $10^{-8} - 10^{-9}$. On the other hand, the difference of $g$-factor between proton and antiproton is known only with the precision of $10^{-3}$. Actually, the $g$-factor of proton is known with a precision of $10^{-8}$ like 5.585694713(46), i.e., this poor comparison originates from the precision of antiproton $g$-factor, which was determined by measuring characteristic X-rays emitted from $\bar{p}$B in circular orbit and by hyperfine transitions of $\bar{p}$He [17]. Accordingly, the first goal is to determine the $g$-factor or the magnetic moment of antiproton with a precision better than $10^{-3}$.

Table 2 shows spectroscopic properties of hydrogen atom, which are one of most precisely known quantities among atoms. It is seen that the $1S$-$2S$ transition is measured with $10^{-14}$ (several tens Hz), and the ground state hyperfine transition is known with $10^{-13}$ (1mHz).

The $1S$-$2S$ transition energy of hydrogen is in the non-relativistic framework given by

$$\nu_{1S,2S} = \frac{3}{4} \frac{m c^2}{2} \left( \frac{q_e q_p}{4 \pi \epsilon_0 \hbar c} \right)^2 = \frac{3}{4} \frac{m (\alpha c)^2}{2}$$  \hspace{1cm} (1)$$

where $m$ is the reduced mass of electron ($m = m_e/(1 + m_e/m_p)$), $m_e$ and $m_p$ the electron and proton masses, $q_e$ and $q_p$ the electron and proton charges, $\epsilon_0$ the dielectric constant of vacuum, and $\alpha$ the fine structure constant. It is seen that the primary factor determining the transition frequency is the electron mass. The proton mass plays a role from $10^{-3}$, and the relativistic as well as the QED effects start to play roles from $10^{-5}$. The present theoretical limit is $10^{-11}$ because of the ambiguity of the proton charge radius.

In the case of the ground state hyperfine transitions, it originates from the interaction between magnetic moments of proton and electron, i.e., this effect gets larger when the overlap of proton and electron is larger like in the case of $S$ state, particularly $1S$ state. The transition frequency between the singlet ($F=0$) and the triplet ($F=1$) states of hydrogen in its ground state is given by

$$\nu_{HF} = \frac{8}{3} \left( \frac{m_p}{m_p + m_e} \right)^3 \frac{m_e \mu_e \mu_p m_e (\alpha^2 c)^2}{m_p \mu_B \mu_N} \frac{\hbar}{h},$$  \hspace{1cm} (2)$$

where $\mu_e$ and $\mu_B = (q_e \hbar/2m_e)$ are the magnetic moment of electron and the Bohr magneton, respectively, and $\mu_p$ and $\mu_N$ are the magnetic moments of proton and nucleon, respectively (the total angular momentum is given by $\vec{F} = \vec{I} + \vec{s}$). It is seen that the hyperfine transition is directly proportional to the magnetic moment of proton, and so is quite suitable to determine
the magnetic moment of antiproton. Considering that $\mu_e/\mu_B$ is -1.0011596521811, eq. 2 can reproduce the observation with a precision of $10^{-5}$, which can be improved to $3.5 \times 10^{-6}$ when the charge and magnetization radius of proton is taken into account. Again, the prediction limit is given by the uncertainty of charge and magnetization distribution of proton [18].

\begin{align*}
\text{(a)} & \quad 2^2S_{1/2} \quad \text{LFS} \\
\text{(b)} & \quad 1S-2S \quad \text{shift} \\
1^2S_{1/2} \quad 1.420 \times 10^{16} \text{Hz} & \quad 1.420 \times 10^{16} \text{Hz} \\
1^2S_{1/2} \quad 2.466 \times 10^{13} \text{Hz} & \quad 0.1 \quad 0.2 \\
0 & \quad 0.1 \quad 0.2 \\
\text{magnetic field [T]} & \quad 10^6 \quad 10^3 \quad 10^1 \quad 10^{-1} \\
& \quad 10^{-3} \quad 10^{-6} \\
& \quad \text{K} \quad \text{T} \\
\end{align*}

\textbf{Figure 1.} (a) Frequency diagram of 1S-2S and ground state hyperfine transitions together with the variation of hyperfine levels as a function of magnetic field. (b) The frequency shift of 1S-2S transition of hydrogen as a function of outer magnetic field as well as the temperature. [24])

The hyperfine levels split into four under magnetic field as is seen in fig.1(a) [19]. Two of them get higher as the outer magnetic field get higher, i.e., they are attracted toward lower field side, and are named as low-field seeking (LFS) states. On the other hand, the levels of the other two get lower as the magnetic field, i.e., they are attracted toward higher field side, and are name high-field seeking (HFS) states. These states can be selected by applying a non-uniform magnetic field like the Stern-Gerlach experiment, and the transition frequencies were determined to be $\nu_{HF} = 1.4204051(2)\text{GHz}$ already a half century ago. The precision of the transition frequency has been improved a lot using a maser scheme, which is given in Table 2 with much higher precision [20].

It is seen from fig.1(a) that the potential energy corresponding to the magnetic field difference of 1T amounts to $\sim 14\text{GHz} \sim 60\mu\text{eV} \sim 0.7\text{K}$. In other words, even for a magnetic trap having a magnetic field difference of 1T is only 0.7K.

\section{3. Antihydrogen Formation Processes}
Potential processes of $\bar{H}$ syntheses are

\begin{align*}
\bar{p} + e^+ & \rightarrow \bar{H} + h\nu \\
\bar{p} + N \hbar\nu & \rightarrow \bar{H} + (N + 1)h\nu \\
\bar{p} + e^+ + e^+ & \rightarrow \bar{H} + e^+ \\
\bar{p} + (e^+ e^-) & \rightarrow \bar{H} + e^+ \\
\bar{p} + A & \rightarrow \bar{H} + e^- + A \\
\end{align*}

These processes can be categorized taking into consideration the way how the energy and momentum conservations are satisfied before and after the reaction. The first and the second processes manage the conservations via photon emission, and are called radiative recombination
and laser-induced recombination processes, respectively. The cross section of the radiative recombination process is proportional to $\rho T^{-1/2}$, where $\rho$ and $T$ are the density and the temperature of positron cloud, respectively. The third process is the three-body recombination process, which depends on $\rho^2 T^{-9/2}$, and becomes the principal mechanism to synthesize antihydrogen when the positron density is high and the positron temperature is low [21]. The fourth process is the collision between antiproton and positronium, the bound state of positron and electron, where the electron in the positronium takes care of the energy and momentum conservations. This can be also regarded as a charge transfer process from a positronium atom. The reaction cross section is as high as $10^{-15}$ cm$^2$ for the ground state positronium, which gets larger for positronium in excited states like $n^4$. It is also noted that the electronic states of antihydrogen can be controlled by tuning the excited level of positronium. A report on the antihydrogen synthesis with positronium was published in 2004 [22]. For all the antihydrogen formation processes discussed above, the energy transfer to the third particle, $E_{\text{tr}}$, is 10eV or lower, and the corresponding momentum transfer is bigger for an electron (positron) emission than a photon emission by a factor of $\sqrt{2m_e c^2/E_{\text{tr}}}$. Accordingly, the final density of state ($\propto \rho^2 dp$) and the reaction rate are also bigger for an electron (positron) as compared with a photon.

The fifth process is in a manner a capture process from a positron sea, where $A$ is an atom, which plays a role of the third particle. Actually, the first antihydrogen production had been demonstrated using this process shooting 1.4GeV antiprotons on Xe gas target in 1996 [23].

4. What to measure
As is seen in Table 2, we have two potential quantities to be measured with high precision so that they can be compared with the corresponding quantities of hydrogen, i.e., 1S-2S transition and ground-state hyperfine transitions of antihydrogen. The former can be realized by trapping antihydrogen atom(s) in a magnetic bottle so that observation time long enough as compared with its lifetime. Figure 1(b) shows the transition frequency shift due to the Zeeman effect and motional Stark effect in outer magnetic field [24]. It is seen that the Zeeman effect dominates the motional Stark effect for the hydrogen temperature below a few K. Considering the fact that the available magnetic bottle till now uses the magnetic field difference less than 1T, which can hold antihydrogen of 0.7K or less, we just need to consider the Zeeman effect, and it amounts as high as $10^9$Hz. Comparing with Table 2, the precision achievable for antihydrogen atoms with 1K is around $10^9$.

5. Cusp Trap Scheme for Microwave Spectroscopy
A field-free region is essential to make high resolution microwave spectroscopy of the ground state hyperfine transitions. In order to make this practically feasible, a potential scheme had been invented employing a pair of anti-Helmholtz coils [5], which is called the cusp trap scheme. The cusp trap scheme opens for the first time a path to realize high precision microwave spectroscopy of ground state hyperfine transitions [5, 14]. An efficient extraction of a spin-polarized $\bar{H}$ beam is the key of the experiment. Figure 2 shows a conceptual drawing of an experimental setup for the microwave spectroscopy of $\bar{H}$ atoms employing the cusp trap scheme, which consists of a cusp trap (the combination of a superconducting anti-Helmholtz coil and a stack of multiple ring electrodes (MRE)), a microwave cavity, a sextupole magnet, and a $\bar{H}$ detector. The cusp trap provides the minimum $B$ field configuration still maintaining axially symmetric magnetic and electric fields. Because of this axial symmetry, the cusp trap realizes stable handlings of both antiprotons and positrons such as trapping, cooling, compression and mixing [25, 26]. Further, $\bar{H}$ atoms in the low-field-seeking (LFS) states are preferentially focused along the cusp trap axis whereas those in the high-field-seeking (HFS) states are strongly defocused, resulting in the formation of an intensity enhanced highly spin-polarized $\bar{H}$ beam [5]. By this way, the microwave cavity can be
Figure 2. A conceptual experimental setup for the ground-state hyperfine transition measurements of $\bar{H}$ atoms with the cusp trap (see the text for more details).

Figure 3. (a) A schematic drawing of the present experimental setup, which consists of the antiproton ($\bar{p}$) catching trap, the compact positron ($e^+$) accumulator, the cusp trap for antihydrogen ($\bar{H}$) synthesis, the 3D track detector, and the $\bar{H}$ detector downstream of the cusp trap. (b) The central part of the cusp trap, which consists of a superconducting solenoid coils, a cryogenic UHC bore tube, and an MRE installed in the bore tube.

installed in a weak uniform magnetic field away from the $\bar{H}$ formation trap, which enables high precision spectroscopy of $\bar{H}$ atoms. Our preliminary simulation revealed that the polarization of 50 K $\bar{H}$ beam amounts to about 30% when they are synthesized near the maximum magnetic field in the cusp trap [27]. The microwave cavity induces hyperfine transitions from LFS to HFS states when the microwave frequency is in resonance. The sextupole magnet sorts out $\bar{H}$ atoms in HFS states from those in LFS states.

Figure 3(a) schematically shows the experimental setup used to confirm the $\bar{H}$ synthesis. It consists of the antiproton ($\bar{p}$) catching trap [28], the compact positron ($e^+$) accumulator [29], the cusp trap, the 3D track detector [30], and the $\bar{H}$ detector. The 3D track detector consisted of two pairs of two modules each having 64 horizontal and 64 vertical scintillator bars of 1.5 cm width. It was used to determine the annihilation position of antiprotons by monitoring charged pion trajectories. Antiprotons of 5.3 MeV from the Antiproton Decelerator (AD) at CERN were extracted into the ASACUSA area, slowed down to 120 keV by a radio frequency quadrupole decelerator (RFQD), and then were injected into the $\bar{p}$ catching trap through a double thin degrader foil of 180 $\mu$g/cm$^2$ thickness. About $10^6$ antiprotons were accumulated and electron-cooled per one AD shot in the $\bar{p}$ catching trap. The antiproton cloud was radially compressed [31]
Figure 4. (a) A drawing of the stack of multiple ring electrodes of the cusp trap (MRE). (b) The magnetic field $B(T)$ along the beam axis. (c) The electric potential $\phi(z)$ along the beam axis. The potential $\phi_1$ for injection of positrons. $\phi_2$ for accumulation and compression of positrons. $\phi_3$ for mixing of antiprotons and positrons. (The mixing region in the upstream part is called the nested trap, and the harmonic part in the downstream is called the field-ionization trap (FIT)). $\phi_4$ for antiproton injection from the upstream side. $\phi_5$ for extraction of antiprotons accumulated in the FIT originating from the field-ionized $\bar{H}$ atoms.

for efficient transportation into the cusp trap.

Figure 3 (b) shows the central part of the cusp trap consisting of superconducting coils ($B_{\text{max}}=2.7T$), an UHV cryogenic bore tube (~6K) [32], an MRE at the center of the coils which was cooled down to ~15K. Upstream of the MRE, a long narrow tube at 50K is prepared to protect the MRE from the room temperature radiation. On the other hand, such a narrow tube is not practical in the downstream of the MRE because $\bar{H}$s should be effectively extracted. A thermal shield flapper was installed at the first cryogenic stage so that it can be open only when $\bar{H}$s are extracted.

Figure 4(a) shows a drawing of the MRE in the cusp trap, which consists of 17 ring electrodes including two four-segmented electrodes (U4 and D4). The ring electrodes have a relatively large inner diameter (80 mm) for efficient extraction of $\bar{H}$ atoms. The MRE and the anti-Helmholtz coil were aligned to the beam axis ($z$-axis) with its central electrode (CE in Fig. 4(a)) at the symmetry point of the cusp magnetic field ($B=0$). Figure 4(b) draws the $z$-component of the magnetic field along the beam axis.

The synthesis and detection of $\bar{H}$ atoms were made as follows:

(i) Positron transport from the $e^+$ accumulator in the upstream part of the cusp trap via the guiding coils (see Fig. 3 (a)) with a potential configuration $\phi_1$ in Fig. 4(c), which was switched back to $\phi_2$ immediately after the injection. Positrons so injected were spontaneously cooled via synchrotron radiation to an environmental temperature within a few seconds and formed a non-neutral plasma. These trapping and cooling procedures can be repeated if necessary. During the accumulation, the positron cloud was continuously compressed employing the rotating wall technique to less than 3 mm in diameter (the density $\rho_{e^+} \sim 10^7$/cm$^3$) [25].

(ii) Smooth variation of the potential from $\phi_2$ to $\phi_3$ (see Fig. 4(c)) keeping the positron cloud
Figure 5. (a) The number of field-ionized antihydrogen atoms accumulated in the FIT every 5s. (b) (c) The annihilation position distributions observed by the 3D track detector for $0 \, s < t < 60 \, s$ and $60 \, s < t < 120 \, s$, respectively. (d) Potential distributions along the z-axis for different bias voltages. The bias voltages were tuned so that the bottom potentials on both sides of the FIT stay constant. (e) The number of field-ionized $\bar{H}$ atoms as a function of the voltage applied on the electrodes D4 and D5 ($V_{FI}$). The solid circles show the experimental results. Seven curves correspond to field-ionization probabilities of $\bar{H}$ atoms calculated for $25 \leq n \leq 55$. The probabilities are scaled to the experimental value at 350 V.

compressed at the center of the nested potential.

(iii) Antiproton injection from the p catching trap (potential $\phi_4$), which is followed by a switch back to $\phi_3$. Antiprotons were then cooled and recombined with positrons. $H$ atoms are not influenced by electric fields formed by the MRE, and a part of them reached the field-ionization trap (FIT). If $H$ atoms were formed via three-body-recombination process in high Rydberg states, they were field-ionized and their antiprotons were accumulated in the FIT [10].

(iv) Repeated openings of the FIT ($\phi_5$ for 100 ms and $\phi_3$ for 5 s) for 20 times. Antiprotons accumulated in the FIT over the 5 s period were released and annihilated each time the FIT was opened.

(v) Kicking out antiprotons toward the upstream of the MRE, and switch back to $\phi_2$. Then the procedure returned to the step (ii) several times for efficient use of positrons.

Figure 5(a) shows the number of events counted by the 3D track detector every 5 s as a function of time since the start of the mixture of $3 \times 10^5$ antiprotons in $3 \times 10^6$ positrons. The number increased in the first 30 s and then slowly decreased in the next 80 s yielding totally 70 events per mixture. Assuming an isotropic angular distribution of $\bar{H}$ atoms and taking into account the solid angle covered by the FIT, the total number of $\bar{H}$ atoms in high Rydberg states was estimated to be about $7 \times 10^3$ per mixture. In other words, the $\bar{H}$ formation efficiency was about 2%.

We changed the number of antiprotons for the same number of positrons to see how it makes a difference to the time dependence of the number of field-ionized $\bar{H}$ atoms. As the number of
antiproton was decreased (increased), the synthesis rate peaked earlier (later) and the synthesis period became shorter (longer). This observation is consistent with an expectation that the cooling of heated positrons proceeds faster for smaller number of antiprotons. We also noticed that the probability of the $\bar{\text{H}}$ synthesis was higher for smaller number of incident antiprotons. For example, the $\bar{\text{H}}$ formation efficiency was about 7% for $4 \times 10^4$ antiprotons. Figures 5(b) and (c) show the annihilation position distribution of antiprotons along the beam axis measured with the 3D track detector for $0 s < t < 60 s$ and $60 s < t < 120 s$, respectively. A sharp single peak is seen in Fig. 5(b) near the positron trapping region. The peak gets broader for Fig. 5(c) with an indication of two bumps near the two potential maxima of the nested trap. The latter observation showed that antiprotons were axially separated from the $e^+$ plasma after several tens of seconds. This axial separation can explain why the $\bar{\text{H}}$ synthesis rate decreased and almost disappeared after 100 s although a large number of antiprotons and positrons were still left in the nested trap.

In order to estimate the principal quantum number $n$ of the synthesized $\bar{\text{H}}$ atoms, the field strength of the FIT was tuned by varying the voltage on the electrodes D4 and D5 for five different fields (see fig. 5(d)). The solid circles in Fig. 5(e) show the number of field-ionized $\bar{\text{H}}$ atoms as a function of the voltage applied to D4 and D5. It is seen that the number of field-ionized $\bar{\text{H}}$ atoms increased as $V_{D4,5}$ increased, and then saturated. We calculated the probability for $\bar{\text{H}}$ atoms to be field-ionized and accumulated in the FIT, assuming they were in a specific $n$ state and drifting out isotropically from the center of the nested trap (a semi-quantitative formula, $F \sim 3.2 \times 10^8 n^{-4}$ (V/cm), were adopted to evaluated the field-ionization, where the influence of the magnetic field is neglected for the sake of simplicity [33], where $F$ is the minimum field strength at which the atom in the $n$ state is field-ionized). Seven curves in Fig. 5(e) show such probabilities for $25 \leq n \leq 55$ taking into account the electric field strength experienced by $\bar{\text{H}}$ atoms along their trajectories in the MRE. The present observation is consistent with the curve for $n \sim 45$ and/or 50. It is noted that $\bar{\text{H}}$ atoms with $n > 55$ are field-ionized by the electric field of the nested trap before they reach the FIT. In the case of three body recombination processes, a typical $n$ can be crudely estimated as $n \sim 400/\sqrt{T(K)}$ by equating the binding energy and the positron temperature. The temperature of the positron plasma during the experiments was then estimated to be several tens of kelvins, which was consistent with a leak mode temperature measurement developed in Ref. [34].

6. Magnetic bottle for antihydorgen toward 1S-2S laser spectroscopy

Figure 6 shows a schematic drawing of the ALPHA setup used to synthesize and trap antihydrogen atoms. The whole setup is installed in a long solenoid, and consists of an antiproton trap, the magnetic bottle to mix antiprotons and positrons and to trap antihydrogen, and a positron trap (from left to right) [35]. Figure 7 (a) schematically shows the structure of the magnetic bottle (the long solenoid for a uniform magnetic field is omitted for the sake of simplicity) [13]. The octupole coil is to give magnetic field gradient in the radial direction, and the pair of mirror coils are to give field gradient in the axial direction. A magnetic bottle is formed by the combination of these fields, which is an Ioffe-Pritchard type trap but employing an octupole coil instead of a usual quadrupole coil. The magnetic field difference is about 0.7T, which can trap antihydrogen as high as ~0.5 K. It is noted that the azimuthal uniformity of the usual Ioffe-Pritchard trap near the magnetic field axis is poor, which results in an instability in storing antiprotons and positrons, the ingredients of antihydrogen. Figure 7(b) shows the field strength variation as a function of radial position. As is clearly seen, the field uniformity near the axis is improved considerably for the octupole field, which results stable confinements of charged particles even when the magnetic bottle is on. Again a nested trap potential configuration is employed, keeping positrons at the center of the potential, and injecting antiproton from the side. In order to mix antiprotons mildly so that colder antihydrogen is synthesized, a so-called
Figure 6. Schematic diagram of the ALPHA apparatus. The graph shows the on-axis longitudinal magnetic field due to the solenoids and mirror coils. The solid (dotted) curve is the field without (with) the inner solenoid. The positron accumulator (not shown) is located to the right of the apparatus. The positrons and antiprotons are held and manipulated in the marked regions before transfer to the mixing section, where further manipulations, including evaporative cooling, are performed.

Figure 7. (a) A schematic drawing of antihydrogen synthesis and trapping region. The atom-trap magnets, the modular annihilation detector and some of the Penning trap electrodes are shown. An external solenoid (not shown) provides a 1 T magnetic field for the Penning trap. Each silicon module is a double-sided, segmented silicon wafer with strip pitches of 0.9mm in the z direction and 0.23mm in the \( \phi \) direction. (b) Magnetic field strength distributions along the radial direction for quadrupole, sextupole, and octupole magnets.

An auto-resonance scheme had been employed, which can induce a center of mass motion without increasing internal temperature of the antiproton cloud very much [36].

When the antihydrogen synthesis reactions are more or less over (about 1s after the mixing started), voltages on the MRE were varied to clean up the magnetic bottle area from bare antiproton and positrons. Then, the octupole coil and the pair of mirror coils were quenched. As soon as the magnetic bottle is opened by the quench, trapped antihydrogen atoms if any would be released and annihilate hitting the inner-wall of the MRE near the magnetic bottle. Repeating such runs, totally 38 trapped antihydrogen events were identified out of 335 trials.
Figure 8. Distributions of released antihydrogen atoms and antiprotons. (a) Measured t-z distribution for annihilations obtained with no bias (circles), left bias (triangles), right bias (inverted triangles). The gray dots are from a numerical simulation of antihydrogen atoms at ground state. The simulated atoms have a maximum kinetic energy of 0.1meV. (b) Experimental t-z distribution, as above, shown along with results of a numerical simulation of mirror-trapped antiprotons. The symbol codes are as above. In both (a) and (b), the simulated z distributions were convolved with the detector spatial resolution of 5mm.

The red inverted triangles, the blue triangles, and the green circles in figs. 8 (a) and (b) show such events as functions of the annihilation position and the time of annihilation since the quench of the magnetic bottle. Different symbols correspond to different electric fields applied. As is seen, the annihilation position did not depend on the electric field configurations. The fine gray dots in fig. 8(a) show the results of simulation assuming antihydrogen atoms were trapped in the magnetic bottle. On the other hand, the blue, green and red dots in fig. 8(b) shows the results of simulation assuming bare antiprotons were trapped in a mirror field for three different electric field configurations. It is apparent that the observed annihilation points and the time since the quench are consistent with the simulation results of trapped antihydrogen but not with those of trapped antiprotons.

7. Summary and Outlook

Recent progress in antihydrogen experiments has been quickly reviewed. The success of the cusp trap scheme opens for the first time a chance to efficiently extract spin-polarized antihydrogen beam in a magnetic-field-free region, which could shortly produce results on the microwave spectroscopy of the ground state hyperfine transitions. The success of the antihydrogen trapping actually enables for the first time to make high precision laser spectroscopy of 1S-2S transition of antihydrogen atoms. Further cooling of trapped antihydrogen atoms would become an important issue to realize high resolution spectroscopy.

It is noted that a spin-flip experiment of a single proton has recently been realized [37], i.e., the same experiment not with proton but with antiproton can shortly be realized, which give information on the difference of the magnetic moments between proton and antiproton, which will be another very stringent CPT symmetry test. In the case of the ground state...
hyperfine transition experiments, not only the magnetic moment, but also the internal structure of the magnetization distribution is obtained, i.e., they are complementary experiments with each other. Further, two projects on the gravitational interaction of antimatter (antihydrogen) - matter (the earth) are in progress. As is well-known, the gravitational interaction is many orders of magnitude smaller than the electromagnetic interaction. Such experiments are therefore quite ambitious and challenging but of considerable interest. Cold antihydrogen research is now at a stage where really interesting experiments on fundamental laws of physics can start.

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