SCOPE FOR HIGH-PRECISION SPECTROSCOPY OF ANTIPROTONIC ATOMCULE AND ANTIHYDROGEN

Toshimitsu YAMAZAKI

Institute of Particle and Nuclear Studies
High Energy Accelerator Research Organization
3-2-1 Midori-cho, Tanashi, Tokyo, 188 and
Japan Society for the Promotion of Science
5-3-1 Koji-machi, Chiyoda-ku, Tokyo, 102 Japan
E-mail: yamazaki@nucl.phys.s.u-tokyo.ac.jp

Future scope of high-precision spectroscopy of antiprotonic atomcules as well as antihydrogen is described from the viewpoints of fundamental physics, such as various CPT invariance tests and test of “anti-gravity”, namely, gravitational force between matter and antimatter.

1. INTRODUCTION

How antiparticles and antimatter behave with respect to their normal partners is an extremely interesting problem. The most fundamental issues are i) CPT invariance tests of various physical quantities and ii) gravitational force between matter and antimatter. To study such properties in laboratory we need antiparticle objects with long enough lifetimes. So far, the best known physical quantities are the charge/mass ratio of antiproton/proton [1] and the $g$-factor ratio of positron/electron [2]. The extremely high precision was brought because they used trapped and cooled antiprotons and positrons which have practically infinite lifetimes as far as they are confined in ultra high vacuum. On the other hand, two- or few-body systems involving one antiproton have very short lifetimes and thus do not allow precise physics. However, there is one exception; antiprotons implanted into helium medium showed an anomalously long lifetime of about $3\times10^6$ s [3,4]. This phenomena is by now well understood in terms of metastable states of large principal ($n$) and orbital ($l$) quantum numbers of antiprotonic helium atom-molecules (in short, atomcule), $\beta e^{-}\text{He}^{2+} (= \beta\text{He}^+)$. In section 2 we discuss the properties of this atomcule and its future project.

The simplest and long-lived antiprotonic system is antihydrogen ($e^+\bar{p}$). Its counterpart, hydrogen, is the most fundamental atom, whose properties have been thoroughly studied by now (see Fig.1). In 1995 antihydrogen was produced and identified for the first time in collision of energetic antiprotons with xenon atoms at LEAR (Low Energy Antiproton Ring) of CERN [5]. However, since such energetic antihydrogen atoms are suitable neither for precision spectroscopy nor for gravitational experiments, efforts to synthesize very low energy antihydrogen atoms from trapped $\bar{p}$ and positrons have emerged and will be continued at the Antiproton Deceleration (AD) Ring, the next generation $\bar{p}$ beam facility being constructed at CERN [6]. In section 3 we discuss some possible experiments in the coming AD era.
II. VARIOUS CPT INVARIANCES

When we can measure a physical quantity $X$ both in the particle and antiparticle sectors, we can obtain a CPT violation parameter

$$\Delta_{CPT}(X) = \frac{X(\text{antiparticle})}{X(\text{particle})} - 1.$$  \hspace{1cm} (1)

We present already known $\Delta_{CPT}$ in Fig. 1.

In what kind of physical observables will a CPT violation be revealed? This is an open and unsolved question, which should be studied theoretically. The absolute value of $\Delta_{CPT}(X)$ does not make sense, because it is ambiguous in definition. For instance, $\Delta_{CPT}$ of the $1s$ binding energy of hydrogen has the same meaning as $\Delta_{CPT}$ of the $1s$ state mass of hydrogen, but its absolute magnitude is by 8 orders of magnitude different. Furthermore, the degree of CPT violation may depend on the nature of the physical observables. For instance, the parity violation dominates only the weak interaction and the CP violation occurs only in the neutral K mesons. Then, in what kind of physical observables should we pursue CPT violation? Nobody knows. So, we have to be open minded to any possible violation.

III. ANTIPROTONIC HELIUM ATOMCULE

The antiprotonic helium atomcule is a unique long-lived interface lying between matter and antimatter. Its structure and level diagram [7,8] are shown in Fig.2. The name "atomcule" originated from the dual nature of this object as an exotic atom and as an exotic molecule. Luckily enough, the metastable states of the atomcule decay by emitting photons in the visible light range, and thus the idea of high precision laser spectroscopy of those metastable states [9] was successfully applied [10].

Theoretical studies of this Coulomb 3-body system also advanced [7,8], and the experimental transition wavelengths are now accounted for by Korobov theory [11] including the relativistic corrections [12] to the level of several ppm, as shown in Fig.3. Further improvements of both experiment [13] and theory [14-16] are expected, which will make it possible to compare the "antiprotonic Rydberg" constant, namely,

$$R_y(\bar{p}) = \frac{M(\bar{p})e^2(\bar{p})}{2\hbar^2}$$ \hspace{1cm} (2)

with the corresponding "protonic Rydberg" constant. Incidentally, the latter quantity itself cannot be measured, since there is no "protonic atom". It can only be calculated by using the known values of the charge and the mass of proton. The very excellent agreement of the transition wavelengths between experiment and theory to the level of a few ppm indicates

$$\Delta_{CPT}(R_y) < 5 \times 10^{-9}.$$ \hspace{1cm} (3)

Hyperfine structure of the atomcule which results from the interaction of the $\bar{p}$ orbital moment and the electron spin has also been revealed [17]. Balaklov and Korobov [18] calculated the hyperfine and superhyperfine (due to the interaction of the $\bar{p}$ spin and the electron spin) coupling constants. Dedicated experiments are planned for the AD era to determine the coupling constants in the quadruplet splitting by laser-microwave triple resonances (see Fig.4) [19]. The predicted values in a typical case are

$$\nu_{HF} = 12.91 \text{ GHz}$$  \hspace{1cm} (4)
$$\nu_{SHF}^4 = 161 \text{ MHz}$$  \hspace{1cm} (5)
$$\nu_{SHF}^6 = 133 \text{ MHz}.$$  \hspace{1cm} (6)

The dominant splitting ($\nu_{HF}$) will bring new information on any anomaly associated with the orbital magnetic moment of $\bar{p}$ and the finer splitting ($\nu_{SHF}$) will yield the spin magnetic moment of $\bar{p}$. Less
precise information has been known for the magnetic moment $\mu_p$ [20] which was deduced from the fine structure splitting of an antiprotonic atom. It is interesting to note that the orbital magnetic moment of proton, $g_p$, has never been measured simply because no "protonic" atom exists (it may exist in an anti-world!).

The present knowledge on the antiprotonic atomcule suggests that the "characteristic" lights of atomcules of wavelengths such as 597 nm and 470 nm might come from somewhere in the universe (such as antimatter fountain, or in the very early stage), where antiprotons form atomcules in normal helium medium (or protons form anti-atomcules in anti-helium medium).

Although the atomcule is an interesting unique object, its life time is limited by radiative decay (a few microseconds). Thus, ultra high resolution spectroscopy and search for anti-gravity will not be possible.

IV. ANTIHYDROGEN SPECTROSCOPY

Since antihydrogen (its ground state) has an infinite lifetime, its high precision spectroscopy will give unprecedented accuracies in terms of CPT symmetry tests and also for its gravitational effect. At the AD of CERN two experimental programs, ATHENA (AD1) [21] and ATRAP (AD2) [22] have been approved.

Both groups are aiming at ultra high resolution spectroscopy of the 1s-2s transition by using Doppler-free two photon (243 nm) excitation, its counterpart being hydrogen spectroscopy, which has already been carried out to high precision by Hänisch's group [23] and Cesar et al. [24]. Since the 2s state has a natural linewidth of 1.3 Hz, one hopes to reach an ultimate precision of $1 \times 10^{-18}$. The problem is thus how to produce antihydrogen atoms of very low energy and how to confine them in a limited spatial region (neutral atom trap).

The 1s-2s transition energy is primarily due to the (electron) Rydberg constant, where the antiproton mass plays a less effective role (3 orders of magnitude). The theoretical uncertainty exists at the level of $1 \times 10^{-11}$ [25] due to the uncertainty in the rms proton radius. In this sense the hydrogen 1s-2s energy yields information on the proton charge distribution.

On the other hand, the hyperfine frequency of the ground state hydrogen is mainly due to the Fermi contact term, given by

$$\nu_{HF} = \frac{16}{3} \left( \frac{m_e}{m_p} \right)^3 \frac{m_e}{M_p} \frac{\alpha^2}{BcRy}.$$  \hspace{1cm} (7)

which is a direct product of the electron magnetic moment and the proton magnetic moment $\mu_p$. Even after higher-order QED corrections [25] a large difference

$$\nu_{HF}(\text{QED}) - \nu_{HF}(\text{Exp}) = 32.55(10) \text{ ppm}. \hspace{1cm} (8)$$

is observed. This discrepancy is accounted for by the non-relativistic size correction (Zemach correction) [25]:

$$\delta_p(\text{Zemach}) = -2m_e\alpha R_{proton}. \hspace{1cm} (9)$$

The most dominant unknown factor is in the magnetic form factor of proton, which gives an uncertainty as much as 1 ppm. Thus, we can say that the hyperfine structure reflects dominantly the magnetic distribution of proton, which is related to the origin of the proton anomalous moment, a current topics of particle-nuclear physics. Thus, the hyperfine structure of hydrogen gives unique information, which is totally different from the binding energies of hydrogen.

The hyperfine structure of the ground state of the hydrogen atom is the best known physical quantity in physics. Its study dates back to early 1930's, when Rabi made a simple configuration of inhomogeneous magnetic field through which spin selected hydrogen atoms were transported. Even from such a primitive experiment a meaningful value of the hyperfine coupling constant was obtained. Throughout its development each new information at every stage was so exciting and productive, influencing the history of modern quantum physics (anomalous proton and deuteron magnetic moments, QED corrections, etc.).
This history is traced vividly in a review article of Ramsey [26]. In the case of antihydrogen spectroscopy we can follow just this development of hydrogen. One could propose the following steps.

a) First step (Magnetic Deflection/Transport)
Spontaneously escaping antihydrogen atoms from any recombination region of antiprotons and positrons are transported by, for instance, a couple of sextupole magnets perpendicular to the trap magnetic field direction, which serve as a velocity and spin selector of antihydrogen atoms (Fig. 5). The identification of antihydrogen atoms thus transported into a free region is easy. In the proposed antihydrogen experiments [21,22] the most difficult problem is how to confine produced antihydrogens, and most people are worried about the escape of antihydrogens from the recombination region, while we can make use of escaping antihydrogens. Such a simple experiment will yield a $10^{-3}$ precision on the $\hbar$fs constant of antihydrogen, better than the poorly known antiproton magnetic moment deduced from the fine structure of an antiprotonic atom ($\sim 3 \times 10^{-3}$ [20]).

b) Second step (Microwave resonance)
Install a microwave cavity of 1.4 GHz in the midpoint between the two sextupole magnets. It will flip the antihydrogen spin. The first sextupole magnet serves as a spin selector and the second one serves as a spin analyzer to detect the microwave resonance. The resonance linewidth depends on the transit time of antihydrogen atoms, and thus on the temperature $T$ of antihydrogens produced. At $T = 4$ K and for a 10 cm length cavity the width is given by

$$\Delta \nu = 2 \text{ kHz}$$  \hspace{1cm} (10)

This resonance spectroscopy will yield precision of $10^{-8}$ fairly easily.

c) Higher precision
To go beyond the conventional limit we need a dedicated instrumentation to enlarge the confinement time in the resonance cavity. This will require cooling of antihydrogen atoms toward lower temperatures and magnetic confinement of antihydrogen atoms.

V. GRAVITATIONAL MOTION

When well cooled antihydrogens are produced, they will be used to study their gravitational motion. For antihydrogen atoms of temperature $T$ (in K)

$$\text{Mean velocity of antihydrogen } v = 130 \ T^{1/2} \text{ m/s}$$ \hspace{1cm} (11)

$$\text{Gravitational acceleration } \Delta v = 4.5 \text{ m/s per m}$$ \hspace{1cm} (12)

$$\text{Magnetic confinement energy } kT = B\mu_B = 0.67 \text{ K/Tesla.}$$ \hspace{1cm} (13)

The most interesting issue here is whether the gravity of antihydrogen embedded in the normal world is qualitatively the same or different. It will open up an exciting research field.

ACKNOWLEDGMENTS

The author would like to thank his colleagues of the CERN PS205 group and Dr. E. Widmann for his help in preparing the figures. The present work is supported by Grants in Aid for Creative Scientific Research of Japanese Monbusho.
REFERENCES

     R.S. Hayano et al., Phys. Rev. Lett. 73 (1994) 1485, 3181(E);
[13] H.A. Torii et al., to be submitted.
FIG. 1. Three experimental values (large numerical letters) of the 1s-2s transition frequency, 2s-2p Lamb shift and the 1s hyperfine frequency of hydrogen are presented together with the theoretical uncertainties. The known information on the CPT symmetry test is also shown.
FIG. 2. (a) The structure of the $\bar{p}\text{He}^+$ atomcule, where the $\bar{p}$ with large $(n, l)$ quantum numbers circulates in a localized orbit around the $\text{He}^{2+}$ nucleus, while the electron occupies the distributed 1s state. (b) The level scheme of large-$(n, l)$ states of the $\bar{p}\text{He}^+$ atomcule. The solid bars indicate radiation-dominated metastable states, while the broken lines are for Auger-dominated short-lived states. The ionized states are also shown by dotted lines.
FIG. 3. Comparison of the wavelength in the zero density limit [13] of a typical transition (39, 35) → (38, 34) with recent theoretical values. The agreement between experiment and theory is excellent when the relativistic as well as the Lamb shift corrections are applied. Three theoretical values by Elander and Yarevsky [14], Kino et al. [15] and Korobov et al. [16] are shown.

FIG. 4. The quadruplet structure of a metastable state of the antiprotonic helium atomcule due to the hyperfine and superhyperfine interactions [18].
FIG. 5. A schematic layout of a simple microwave resonance experiment for antihydrogen. The antihydrogen atoms, which are produced in the central region of a charged particle magnetic trap, are transported via a couple of sextupole magnets. Spin selected antihydrogen atoms in the first sextupole magnet enter a microwave cavity and spin-flipped atoms are analyzed in the second magnet.