Precision spectroscopy of antiprotonic atoms

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Abstract

Precision spectroscopy of antiprotonic atoms will be an important subject to be pursued at the new antiprotonic decelerator (AD) facility being completed at CERN. In particular, the study of antiprotonic helium atoms, \( p^+\text{He}^+ \equiv \text{pHe}^+ \), first discovered at KEK and studied in detail at low-energy antiproton ring (LEAR), will continue to be one of the most important subjects at AD. Our recent high-resolution laser spectroscopy of \( p\text{He}^+ \) has reached a precision of 0.5 ppm, and the agreement between our experimental values of transition energies and the calculations has become better than 1 ppm. This agreement in turn sets a severe constraint on the antiproton charge and mass. Future possibilities at AD will be discussed.

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1. Introduction

In this paper, I would like to discuss the present status and future directions of precision laser spectroscopy of three kinds of exotic atoms containing antiprotons shown in Fig. 1: (i) antiprotonic helium \( (p\text{He}^+ \equiv \text{pHe}^+) \); (ii) protonium \( (\bar{p} - p) \); (iii) antihydrogen \( (\bar{p} - e^+) \).

Study of exotic atoms has contributed greatly to the measurement of masses and magnetic moments of various particles, test of conservation laws and symmetries, study of nuclear properties and so on. The high-precision study of antiprotonic atoms was pioneered at CERN low-energy antiproton ring (LEAR); the success of the laser spectroscopy of \( p\text{He}^+ \), as described later, opened up a new frontier. Although LEAR was prematurely shut down at the end of 1996, the study of antiprotonic atoms will be continued at antiproton decelerator (AD), a new low-energy antiproton source being completed at CERN.

The study of antiprotonic atoms at AD will make it possible for us to better understand the symmetry between matter and antimatter. In addition, atomic processes involving slow antiprotons, such as ionization and atomic capture are interesting subjects which can only be studied at AD. Our collaboration, called atomic spectroscopy and collisions using slow antiprotons (ASA-CUSA), will extend our frontier of low energy antiproton physics [1].
As shown in Fig. 2, ASACUSA will evolve in three phases. In the first phase, we will use the direct $\bar{p}$ beam from AD at 5.3 MeV and will concentrate on the laser and microwave spectroscopy of $\bar{p}$He$^+$. In the second phase, we will add an RFQ linear decelerator, which will decelerate antiprotons from 5.3 MeV to few tens of keV. This will enable us to study antiprotonic atom formation in very dilute gases and will also make it possible to measure antiprotonic energy loss in various materials to $\sim$1 keV. In the third phase, another powerful device, an antiproton trap will be installed downstream of the RFQ. Antiprotons will be captured and cooled (by collisions with electrons) in the trap and will be extracted at and below $\sim$1 keV (eventually down to $\sim$10 eV). With such ultra-low-energy beam, hitherto impossible to obtain, it will become possible to produce antiprotonic atoms in a single-collision environment, i.e., in $\sim$ vacuum, to study their production mechanisms in detail and also to perform high-precision spectroscopy.
2. Antiprotonic helium

Antiprotonic helium (pHe⁺) is an exotic three-body metastable system consisting of an antiproton, an electron and an alpha particle. We first noticed its existence at KEK when we found that about 3% of antiprotons stopped in liquid helium survived with a lifetime of about 3 μs [2]. Subsequently, we measured at LEAR delayed annihilation time spectra (DATS) of antiprotons in various helium media [3] and found that the longevity persists over a wide range of the target helium density (solid to gas).

After an antiproton is captured on a helium atom by replacing one of the two electrons, the p usually cascades down by ejecting the remaining electron and an ionized pHe⁺‡ is formed. This ion is quickly quenched by the Stark collision, leading to the prompt annihilation of p (see Fig. 3). This is the fate of ~97% of antiprotons stopped in helium. However, if the p possesses a large principle quantum number of n ≥ 38 and a large orbital angular momentum l ≥ n − 1, Auger transitions are much suppressed. Radiative transitions, which tend to follow the v = n − l − 1 = constant propensity rule, are typically ~1 μs per step, and the electron which remains, protects the system against quenching collisions. Hence, a three-body neutral pHe⁺ atom becomes metastable. Due to its long lifetime, it has become possible to study this atom in detail using a powerful method of high-precision laser spectroscopy.

2.1. Laser spectroscopy of pHe⁺

Fig. 4 shows the level scheme of large-(n, l) states of pHe⁺. The solid lines indicate radiation-dominated metastable states, while the broken lines are for Auger-dominated short-lived states. Around n ~ 38, where antiprotons are initially captured, the Δn = 1 level spacing is about 2 eV, hence tunable lasers can be used for high precision studies.

The laser spectroscopy method we developed [4,5] is to induce a laser-resonant transition between a metastable level and a short-lived level (for example, (n, l) = (39, 35) → (38, 34)). We stopped the 200 MeV/C antiprotons from the LEAR storage ring in a cryogenic helium gas target (typically cooled to 5 K at 0.5 bar). For each incoming p with no prompt annihilation, we assumed that a metastable pHe⁺ was formed in the target, triggered a tunable pulsed dye laser, and measured the annihilation time spectrum. This was repeated until enough (~10⁵–6) events were recorded, when we stepped the laser to the next wavelength.

In 1993, we succeeded for the first time to observe a laser resonant transition at 597 nm ((n, l) = (39, 35) → (38, 34)), see Fig. 5) [6], after about a week of scanning around the theoretically predicted wavelengths, which typically had precisions of about 1000 ppm. In 1995, when Korobov achieved a much better precision of 50 ppm [7], our resonance search was greatly accelerated, and we have so far measured the 13 transitions shown in Fig. 6. The agreement between experiment and theory became better than about 5 ppm when relativistic corrections were included [8].

2.2. Antiproton Rydberg constant

At this point, we improved the band width of our laser system and performed a more careful scan of the resonance lines. We then found that the resonance vacuum wavelengths for the known
Fig. 5. The first observation of laser-induced resonant annihilation in metastable antiprotonic helium atoms. The resonance, observed at 597 nm, was assigned to the $n_{39}; l^* \rightarrow n_{38}; l^*$ transition. Spikes due to forced annihilation through the resonance transitions are seen at 1.8 $\mu$s, when the laser wavelength is adjusted to hit the resonance.

Fig. 4. The level scheme of large-$n; l^*$ states of $^3$He$^+$. The solid lines indicate radiation-dominated metastable states, while the broken lines are for Auger-dominated short-lived states. Laser-induced resonant annihilation can be observed by ‘shooting down’ antiprotons from one of the metastable states to a short-lived state.
transition $^{39}_{35}$ \rightarrow $^{38}_{34}$ depend linearly on the target helium density [9]. Hence, when we compare the experimental values with results of theoretical calculations, we must take the zero-density limit. The wavelength extrapolated to zero-density limit for the $^{39}_{35}$ \rightarrow $^{38}_{34}$ transition was found to be $\lambda_0 = 597.2570 \pm 0.0003$ nm (Fig. 7).

This value, with a 0.5 ppm precision, was compared with the result of recent theoretical calculations [8,10–13] on the energy of the Coulombic three-body system (see Fig. 5), including relativistic corrections and the Lamb shift. The estimated theoretical error is now smaller than 20 ppb (about 13 ppb is due to the non-relativistic three-body calculation uncertainty, and the rest is due to uncertainty in relativistic corrections) [13]. The agreement between our experimental values and the calculations is better than $1 \times 10^{-6}$. This excellent agreement in turn provides a precise value of the antiproton Rydberg constant that

Fig. 6. Comparison of the experimental wavelengths of various transitions with Korobov predictions (closed squares without [7] and closed triangles with [8] relativistic corrections). The upper part is for $\Delta v = \Delta(n - l - 1) = 0$ intraband transitions and the lower part is for $\Delta v = 2$ interband transitions. The error bars are the experimental ones.

Fig. 7. Experimental values of the vacuum wavelengths for the transition $^{39}_{35}$ \rightarrow $^{38}_{34}$ compared with recent theoretical values.
surpasses the currently known precision of 50 ppm, and sets a severe constraint on the antiproton charge \((-Q_p)\) and the mass \((M_p)\) that both \(|Q_p - Q_p|/e\) and \(|M_p - M_p|/M_p\) be less than \(5 \times 10^{-7}\), when a more precisely known constraint on the charge-to-mass ratio \([14]\) is combined.

If we assume the CPT invariance between the properties of the proton and the antiproton, as the theoretical calculations do, the agreement is a signature of the excellence of theoretical treatments and calculation techniques of the Coulombic three-body system including QED corrections. On the other hand, if we take the calculation results for granted, this in turn gives a stringent test of the fundamental constants of the antiproton and therefore tests the CPT theorem. We have thus opened a new possibility of determining fundamental constants of the antiproton.

3. Future experiments at CERN AD

3.1. Antiprotonic magnetic moment

One of the first important experiments of ASACUSA at AD is to precisely measure the hyperfine splitting of antiprotonic helium. Although we have already succeeded to resolve the 1.7 GHz hyperfine splitting in the \((37, 35) \rightarrow (38, 34)\) laser transition with a precision of about 3% \([15]\) (see Fig. 8), we plan to achieve a much higher precision of \(<10^{-4}\) at AD, using a laser–microwave resonance technique.

While the laser scan measured the difference between \(f_+\) and \(f_-\) (see Fig. 8 for the notations), our planned experiment will induce a microwave resonant transitions, \(v_{HF}^+\) and \(v_{HF}^-\), predicted \([8]\) to be at \(~13\) GHz for \((n, l) = (37, 35)\). Once we succeed to observe these resonances at \(~13\) GHz, we shall proceed one step further to study the \(v_{SHF}^+\) and \(v_{SHF}^-\) transitions, which give direct information on the antiprotonic magnetic moment.

3.2. Higher-resolution study of antiprotonic helium laser transitions

Until recently, it was not at all clear whether or not the laser spectroscopy of antiprotonic helium atoms can be used for the high-precision study of antiprotonic properties, since we must always rely on rather complicated three-body theories to extract information on, for example, antiprotonic mass or charge. Theoretical progress of the past two years has been quite remarkable, and the accuracy of calculating the transition energies, with all the relevant relativistic as well as QED corrections, will soon reach the relative precision of \(10^{-10}\) or better \([13]\). This new development clearly motivates us to push the high-precision frontier of antiprotonic helium spectroscopy to its limit. Technically, the precision is, and will be, limited by the bandwidth of the pulsed laser. With our present laser system (excimer- or Yag-pumped dye lasers), the band width is about 1 GHz, hence the precision is limited to about 0.1–0.5 ppm. By using
the pulse-amplified CW lasers, it should be possible to reduce the band width by more than an order of magnitude and to reach the precision of a few tens of ppb or better. This is clearly an important goal to be pursued by the ASACUSA collaboration at AD.

3.3. Protonium

When an ultra-low-energy antiproton beam extracted from the trap becomes available, many new experiments will become possible, and production and spectroscopy of protonium ($pp$) in a near-vacuum condition is one of the interesting possibilities. It is well known that protoniums produced in gaseous hydrogen are quickly quenched by Stark collisions. However, if we can make protoniums in vacuum, for example by colliding ultra-slow $p$'s on an atomic gas jet target, protoniums can only deexcite by slow radiative transitions and should be quite long-lived.

We show in Fig. 9 a possible scheme to carry out the laser spectroscopy of protonium. The method comprises the following steps:
1. Ultra-slow antiprotons ($E_p \sim 30$ eV) are extracted from a catching trap, hit an atomic hydrogen gas target and form protoniums. The kinetic energy of antiproton is adjusted to populate $n \sim 40$ for which the lifetime is a few microseconds. The density of the atomic target is low enough so that Stark collisions, which is the dominant quenching process in $H_2$ target, are unimportant.
2. Protoniums are selectively excited by two counter-propagating laser beams to $n = 84$, where the lifetime exceeds 100 $\mu$s.
3. On-resonance protoniums survive the 1 m flight path ($\sim 30$ $\mu$s flight time) and are detected with the annihilation detector placed at the end of the flight path, but off-resonance protoniums annihilate in flight and do not reach the detector. By counting the number of protonium arriving at the detector as a function of laser frequency, we can determine the protonium energy level spacings.

Here again, the resolution is limited by the bandwidth of the pulsed laser. The ultimate precision will be a few tens of ppb.

3.4. Antihydrogen

At AD, there are two approved antihydrogen experiments, ATRAP [16] and ATHENA [17]. Although there are many technical differences, they both use Penning traps to catch and cool antiprotons, and then try to merge the cooled antiprotons with a cloud of cold positrons. They will then precisely measure the $1S-2S$ transition and compare its frequency with that of hydrogen and to test the CPT symmetry with high-precision; for hydrogen, the $1S-2S$ transition frequency has been measured with an astounding precision of 14 digits [18].

4. Summary

Very low energy antiprotons produced at CERN AD using the RFQ (and the trap in the future) will make it possible to pursue the high-precision frontier of antiprotonic atom spectroscopy. The study of antiprotonic helium, in particular, will contribute to the stringent CPT test, and it will also serve as a benchmark of the state of the art of the three-body QED calculations. At the same time, the study of antiproton collisions on simple atoms such as hydrogen or helium will provide crucial information to test three-body theories involving continuum states.
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