High-precision laser spectroscopy of antiprotonic helium atoms

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The antiprotonic helium, $\bar{p}e^{-} \text{He}^{2+} \equiv \bar{p}\text{He}^+$, first discovered at KEK and studied in detail at LEAR, is a unique metastable existence interfacing between matter and antimatter. Our recent high-resolution laser spectroscopy of $\bar{p}\text{He}^+$ 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 the new antiproton decelerator (AD) are also discussed.

1. INTRODUCTION

Antiprotonic helium ($\bar{p}\text{He}^+$) is an exotic 3-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 $3 \mu s$[1]. Subsequently, we measured at LEAR delayed annihilation time spectra (DATS) of antiprotons in various helium media[2], 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 $\bar{p}$ usually cascades down by ejecting the remaining electron, and an ionized $\bar{p}\text{He}^{++}$ is formed. This ion is quickly quenched by the Stark collision, leading to the prompt annihilation of $\bar{p}$. This is the fate of $\sim 97\%$ of antiprotons stopped in helium. However, if the $\bar{p}$ possesses a large principle quantum number of $n \sim 38$ and a large orbital angular momentum $l \sim n-1$, Auger transitions are much suppressed. Radiative transitions, which tend to follow the $v = n - l - 1 =$ constant propensity rule, are typically $\sim \mu s$ per step, and the electron which remains protects the system against quenching collisions. Hence a three-body neutral $\bar{p}\text{He}^+$ 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. LASER SPECTROSCOPY

Fig. 1 shows the level scheme of large-($n, l$) states of $\bar{p}\text{He}^+$. The solid lines indicate radiation-dominated metastable states, while the wavy lines are for Auger-dominated short-lived states. Around $n \sim 38$, where antiprotons are initially captured, the $\Delta n = 1$ level spacing is about 2 eV, hence tunable lasers can be used for high precision studies.
Figure 1. The level scheme of large-(\(n, l\)) states of the \(\bar{p}\)He\(^+\) atomcule. The solid lines indicate radiation-dominated metastable states, while the wavy 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.

The laser spectroscopy method we developed\[3\] is to induce a laser-resonant transition between a metastable level and a short-lived level (for example, \((n, l) = (39, 35) \rightarrow (38, 34)\)). 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 \(\bar{p}\)He\(^+\) was formed in the target, triggered a tunable pulsed dye laser, and measured the annihilation time spectrum. This was repeated until enough (\(\sim 10^5\)–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) \(\rightarrow\) (38, 34), see Fig. 2)\[4\], 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\[5\], our resonance search was greatly accelerated, and we have so far measured the 13 transitions shown in Fig. 3. The agreement between experiment and theory became better than about 5 ppm when relativistic corrections were included\[6\].

3. ANTIPROTONIC RYDBERG

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 transition \((39, 35) \rightarrow (38, 34)\) depend linearly on the target helium density\([7]\) (theoretical accounts of the density dependence of the energy levels and widths are discussed by Korenman\([8]\) and by Bakalov\([9]\)). 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.

This value, with a 0.5-ppm precision, was compared with the result of recent theoretical calculations\([6,10–12]\) on the energy of the Coulombic three-body system (see Fig. 5), including relativistic corrections and the Lamb shift. 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 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 \(|Q_p - Q_{cp}|/e\) and \(|M_p - M_{cp}|/M_p\) be less than \(5 \times 10^{-7}\), when a more precisely known constraint on the charge-to-mass ratio\([13]\) 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
Figure 5. The progress of laser spectroscopy of $\bar{p}\text{He}^+$, both experimental and theoretical, over the past several years, plus some future prospects.

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.

4. ASACUSA AT CERN AD

Although LEAR was prematurely shut down at the end of 1996, a new antiproton decelerator (AD) will start its operation in the fall of 1999. One of the first important experiments proposed by the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration[14] 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], we plan to achieve a much higher precision of $< 10^{-4}$ at AD, using a laser-microwave resonance technique.

We also plan to make an ultra low energy ($E_\pi \sim 10 - 1000\text{eV}$) antiproton beam using an RFQ linear decelerator and an antiproton catching trap. It will then become possible to make antiprotonic helium and other species of antiprotonic atoms in a near-vacuum
condition, perform a much higher precision spectroscopy of these atoms, and to determine antiprotonic charge, mass and magnetic moment with high precision.

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