Study of the hyperfine structure of antiprotonic helium

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Abstract

The metastable states of antiprotonic helium have a unique magnetic substructure called hyperfine structure, arising from the coupling of the large angular momentum of the antiproton \((l \sim 35)\) with the electron and antiproton spins. We designed, developed and performed a laser-microwave-laser resonance spectroscopy experiment to investigate this hyperfine structure. We observed two microwave transitions, and the measured frequencies agree well with recent theoretical calculations. To investigate possible collision-induced shifts of the transition frequencies, we measured the microwave transition frequencies at two different target densities. Within the limited statistics, we did not observe a clear sign of a density shift, in accordance with a theoretical estimate by Korenman. When averaging the transition frequencies over the density, we reach an agreement of about 60 ppm with the three-body QED calculations, which is of the same order than the accuracy of the calculations, and slightly larger than the experimental precision.

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1. Introduction

Antiprotonic helium \((p^e\text{He}^2^+ \equiv pH^+)\) is a metastable three-body system consisting of an electron, a helium nucleus and an antiproton, which has a series of long-lived \((\tau \sim \mu s)\) states with principal quantum number \(n\) and angular momentum quantum number \(l\) in the range 33–39. It provides a good test field for three-body QED calculations since we can study its energy structure by precision spectroscopy [1,2].

The hyperfine structure (HFS) of \(p^e\text{He}^+\) arises from the interaction of the magnetic moments of the antiproton \(\vec{\mu}_p\) and the electron \(\vec{\mu}_e\). \(\vec{\mu}_p\) is dominated by the orbital magnetic moment \(\vec{\mu}_p^o = g_p^o \vec{l}_\pi\), where \(g_p^o\) is the orbital \(g\)-factor of the antiproton.
and the omission of terms of order uncertainties, the overall error being determined by on three-body QED theory \[4–6\]. The latest calculation methods had been well tested in the case of the E1 transition frequencies \[1\] where spin effects are small. For the spin-dependent values required. Therefore we planned an experiment to directly measure the hyperfine structure of the state \((n, l) = (37, 35)\). Just by laser spectroscopy we can only measure the difference of the hyperfine structures of the initial state \(v_{HF}\) and the final state \(v'_{HF}\), and not the splitting \(\Delta v_{HF}\) itself. Furthermore, the superhyperfine structure cannot be observed by laser spectroscopy since the precision of the measurement is limited by the laser bandwidth which is as large as ~600 MHz. To overcome these problems a new method to directly measure \(v_{HF}\) was required.

Here we report the experimental results of our laser-microwave-laser spectroscopy of the hyperfine structure of \(p\text{He}^+\) performed in 2001 at CERN’s Antiproton Decelerator (AD). The first report \[7\] was made under the assumption that there is no density dependence of the microwave transition frequencies, and the results were given by averaging all our data taken at different densities. In this report we discuss the possible effect of the target density on the determination of the transition frequencies. According to a theoretical prediction \[8\] based on atomic collision theory the density shift of the microwave transition is negligible (\(\Delta \nu \leq 66 \text{ kHz}\)), while the broadening of the resonance lines is not. Yet we know that E1 laser transitions show a strong density shift \[1,2\]. It is therefore interesting and also essential for the high-precision determination of the hyperfine transition frequencies to study possible density-induced shifts or broadening of the resonance lines.

2. Laser-microwave-laser resonance spectroscopy method

For the direct measurement of \(v_{HF}\) of the metastable state \((n, l) = (37, 35)\), we induce microwave transitions of frequency ~12.9 GHz within the hyperfine quadruplet. More details of the experimental setup are described in \[7\]. Pulses containing \((2–4) \times 10^7\) antiprotons of momentum 100 MeV/c from the AD of CERN were stopped every 2 min in helium gas kept at 6.1 K and
pressures of 250 or 530 mbar. Inside the cryogenic helium target region we prepared a microwave cavity with a resonance frequency of \( \sim 12.9 \text{ GHz} \), and generated a microwave field from a travelling wave tube amplifier outside the cryostat.

There are two allowed M1 transitions, one from \( (F,J) = (l - 1/2, l) \) to \( (l + 1/2, l + 1) \) (\( \nu_{\text{HF}}^+ \)) and one from \( (l - 1/2, l - 1) \) to \( (l + 1/2, l) \) (\( \nu_{\text{HF}}^- \), cf. Fig. 1). To detect a population transfer caused by the resonant microwave radiation, a population asymmetry should exist within the quadruplet before application of the microwave. Fig. 2 shows a diagram of the simulated state populations during the laser-microwave-laser experiment. Just after the formation of the \( ^{3}P_2 \text{He}^+ \) atoms in the helium medium, each quadruplet state is almost equally populated. As a first step, we shoot a narrow-band laser pulse onto the atoms with a frequency of \( f^+ \) (see Fig. 1) at time \( t = t_1 \) and cause resonant transitions to the short-lived state \( (n,l) = (38,34) \) only for the atoms in \( F^+ \) states. This creates a population asymmetry between \( F^- \) and \( F^+ \).

After \( \sim 150 \text{ ns} \) exposure to the microwave field we shoot a laser pulse of the frequency \( f^+ \) again at \( t = t_2 \). The metastable atoms in \( F^+ \) are forced to annihilate through the short-lived state, emitting mesons from the annihilations. We can count the meson emissions (hence \( \text{pHe}^+ \) annihilations) by \( \text{Cerenkov} \) counters, and probe the population in the \( F^+ \) states. If a resonant microwave transition from \( F^- \) to \( F^+ \) occurred in the second step (case (b) in the figure), the population of \( F^+ \) should become larger than that in the no-microwave case (case (a) in the figure). We measured the intensities \( I \) of the laser peaks at \( t_2 \) and \( t_1 \) while keeping the laser frequency constant and scanning the microwave frequency \( \nu_M \). If the microwave frequency coincides with the M1 transition frequencies \( \nu_{\text{HF}}^+ \) or \( \nu_{\text{HF}}^- \), the annihilations induced by the second laser pulse should increase compared to the case with off-resonant \( \nu_M \).

3. Experimental results and conclusions

We obtained the resonance profile of the microwave transition by plotting the intensity ratio \( I(t_2)/I(t_1) \) as a function of \( \nu_M \), and determined the microwave transition frequencies by fitting two Lorentzians of equal width and height to the data. Fig. 3 shows the experimental results of the microwave transition frequencies \( \nu_{\text{HF}}^+ \) and \( \nu_{\text{HF}}^- \). Here each data point is obtained from a one-day (i.e. 8-h) data taking period with constant target gas density, yielding an error of 300–400 MHz. In all cases both transition frequencies are close to the corresponding theoretical values based on latest three-body QED calculations \([5,6]\), which are

![Figure 2](image_url)

Fig. 2. Simulated time evolution of the populations of each SHF sub-state for \( (n,l) = (37,35) \) and of the short-lived daughter states of \( (n,l) = (38,34) \) representing the observed \( \text{p} \) annihilation rate: (a) no microwave case and (b) resonant microwave radiation of \( \nu_M = \nu_{\text{HF}}^+ \) is applied. The shaded area at \( t = t_2 \) in (b) corresponds to the peak in case (a), indicating that the short-lived states in case (b) have a larger population due to the microwave transition. The areas are not drawn to scale.
Fig. 3. The results of the resonance frequencies of each day against the helium target density. The solid lines show the experimental values obtained by averaging of each data. The dashed lines show theoretical values. The light-gray bands show the range of theoretical values including their 50 ppm error.

indicated with dashed lines in Fig. 3. As can be seen from Fig. 3, the data points do not show a significant density dependence. However, due to the limited statistics for each data point, and the fact that we measured only at two different densities, we cannot rule out the existence of a small shift.

The experimental result of a small density shift is in agreement with the prediction by Korenman et al. [8]. His value of $D_m^K = 66$ kHz, however, is much smaller than our experimental accuracy of a few 100 MHz. The width of each resonance line varies between $\Gamma_{\text{exp}} \sim 3$–8 MHz, with a large error of $\pm 1$ MHz. These values are comparable to the prediction of Korenman et al. of $\Gamma_{\text{th}} \lesssim 5.8$ MHz.

Assuming a density dependence that is much smaller than our experimental error, we can deduce the overall results of the transition frequencies by averaging over all experimental values regardless of the target density. The resulting values of $v^+_{\text{HF}} = 12.89596 \pm 0.00034$ GHz and $v^-_{\text{HF}} = 12.92467 \pm 0.00029$ GHz correspond to the horizontal solid lines and were published in [7]. The agreement between the averaged experimental values and the calculations is $\sim 60$ ppm, while the uncertainty of the calculations is of the order $\sim 50$ ppm, slightly larger than the experimental error of $\sim 30$ ppm. Thus the validity of the three-body QED theories was proved to this level. The agreement between experiment and theory also confirms the relation $g_p^p = 1$ assumed in the calculations with a relative precision of $\sim 6 \times 10^{-5}$. This is the first measurement of the orbital $g$-factor for both the proton and the antiproton, since no atoms with orbiting protons exist in our world.

The difference $\Delta \nu_{\text{SHF}} = v^+_{\text{HF}} - v^-_{\text{HF}}$ is caused by the SHF splitting and is directly proportional to the spin magnetic moment $\vec{\mu}_p = g_p^p S_p / \gamma_p$, which is known experimentally only to $0.3\%$ [9]. An improvement of the experimental precision for $\Delta \nu_{\text{SHF}}$ by a factor of 5 will be necessary to improve this value. More studies of the density shift of the transitions frequencies are planned in the near future as part of an attempt to increase the experimental accuracy.

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