Spectroscopy of the hyperfine structure of antiprotonic ^4He and ^3He

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Abstract The spin magnetic moment $\mu_s^{\bar{p}}$ of the antiproton can be determined by comparing the measured transition frequencies in $\bar{p}^4\text{He}^+$ with three-body QED calculations. A comparison between the proton and antiproton can then be used as a test of CPT invariance. The highest measurement precision of the difference between the proton and the antiproton spin magnetic moments to date is 0.3%. A new experimental value of the spin magnetic moment of the antiproton was obtained as $\mu_s^{\bar{p}} = -2.7862(83)\mu_N$, slightly better than the previously best measurement. This agrees with μ_s^p within 0.24%. In 2009, a new measurement with antiprotonic ^3He has been started. A comparison between the theoretical calculations and experimental results would lead to a stronger test of the theory and address systematic errors therein. A measurement of this state will be the first HF measurement on $\bar{p}^3\text{He}^+$. We report here on the new experimental setup and the first tests.

Keywords Antiproton · Antiprotonic helium · Hyperfine structure · Spectroscopy · Laser · Microwave · Three-body quantum electrodynamics

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1 Introduction

Antiprotonic helium has been measured for the first time at KEK in Japan in 1991 [1]. It was observed that antiprotons which are slowed down and stopped in a helium target will form *antiprotonic helium* and survive several microseconds. If an antiproton is approaching a helium atom at its ionization energy (24.6 eV) or below, the antiproton can eject one of the two electrons in the ground state from the helium atom, replace it and thus get captured. This exotic, metastable three-body system, consisting of one electron in the ground state, the helium nucleus and the antiproton precessing around the nucleus, is called antiprotonic helium [2–4]. They occupy circular states with $n \sim l$, where l is the angular momentum quantum number. The electron remains in the ground state. The antiproton is, due to its high mass, most likely to occupy states with high angular momentum, i.e. a principal quantum number $n = n_0 \equiv \sqrt{M^*/m_e} \sim 38$, M^* being the reduced mass of the system. As this neutral system retains one electron, it is further protected from collisions with external atoms by the Pauli exclusion principle. The external Auger decay of the remaining electron is suppressed by the large ionisation energy compared to the $n \rightarrow n - 1$ level spacing of a few eV. The presence of the electron also removes the l -degeneracy of the states with the same n , therefore protecting them against Stark mixing. About 97% of these exotic atoms find themselves in states dominated by Auger decay and ionize within nanoseconds (~ 10 ns) due to the Auger excitation of the electron. Stark mixing occurs due to the induced electrical field of the ions. The antiprotons then decay within picoseconds and annihilate with one of the nucleons of the helium nucleus because of the overlap of their wavefunctions. Only a small fraction of 3% of antiprotonic helium atoms remain in metastable, radiative decay dominated states with energy level spacings of ~ 2 eV. Δl is large and thus Auger decay is suppressed. Therefore, these states are relatively long lived having a lifetime of about 1.5 microseconds before they also decay. This small time window can be used to do the measurements of the hyperfine structure. At the end of the cascade, when Auger decay is no longer suppressed, the second electron is ejected in less than 10 ns, degeneracy occurs, Stark mixing becomes dominant and the antiproton annihilates in the nucleus.

2 The hyperfine structure of antiprotonic helium

The interaction of the magnetic moments of its constituting particles gives rise to a splitting of the energy levels. The coupling of the electron spin $\vec{S}_e$ and the orbital angular momentum of the antiproton $\vec{L}$ leads to the primary splitting of the state into a doublet structure, in the order of $\nu_{\text{HF}} = 10 - 15$ GHz. This spin-orbit splitting is referred to as *hyperfine* (HF) splitting. The spin-orbit interaction of the antiproton orbital angular momentum and antiproton spin $\vec{S}_{\bar{p}}$ in combination with the contact spin-spin and the tensor spin-spin interactions between the particles result in a further splitting of these HF states into quadruplets, the so-called *super-hyperfine* (SHF) splitting, of about $\nu_{\text{SHF}} = 150 - 300$ MHz. In antiprotonic ^4He the nucleus has no spin and thus there is only a quadruplet substructure, while for ^3He a nuclear spin exists which also couples with electron and antiproton magnetic moment. Thus, one obtains a further substructure and a splitting into eight SHF substates instead of

Fig. 1 Hyperfine structure of $\bar{p}^4\text{He}^+$ (left) and $\bar{p}^3\text{He}^+$ (right)

four. The overlap with the electron cloud is larger for the helium nucleus even though the magnetic moment is smaller than that of the antiproton. As a consequence, the helion contributes to the superhyperfine structure while the antiproton spin causes the *super-super-hyperfine* (SSH) splitting. Figure 1 shows the energy level structure for $\bar{p}^4\text{He}^+$ and $\bar{p}^3\text{He}^+$.

The dominant hyperfine splitting can be described by the quantum number $\vec{F} = \vec{L} + \vec{S}_e$, defining $F_+ = L + \frac{1}{2}$ and $F_- = L - \frac{1}{2}$. The SHF quadruplet is written as $\vec{J} = \vec{F} + \vec{S}_{\bar{p}}$ for $\bar{p}^4\text{He}^+$. In the case of $\bar{p}^3\text{He}^+$ the quadruplet is described as $\vec{G} = \vec{F} + \vec{S}_h = \vec{L} + \vec{S}_e + \vec{S}_h$ and the octet as $\vec{J} = \vec{G} + \vec{S}_{\bar{p}} = \vec{L} + \vec{S}_e + \vec{S}_h + \vec{S}_{\bar{p}}$, where S_h defines the additional spin of the helium nucleus. Transitions between those SHF and SSHF states can be induced by a microwave frequency field. Only the transitions which include a single electron spin flip, referred to as *favoured* transitions, are measured due to limitations of microwave input power. The *unfavoured* transitions consisting of an electron and an antiproton spin flip would require considerably more power. The electron spin flip transitions can be induced by an oscillating magnetic field. The allowed transitions are given below. There are two for $\bar{p}^4\text{He}^+$

$$\begin{aligned} \nu_{HF}^+ : J^{++} = F^+ + \frac{1}{2} &\leftrightarrow J^{-+} = F^- + \frac{1}{2} \\ \nu_{HF}^- : J^{+-} = F^+ - \frac{1}{2} &\leftrightarrow J^{--} = F^- - \frac{1}{2} \end{aligned} \quad (1)$$

and four transitions for $\bar{p}^3\text{He}^+$

$$\begin{aligned} \nu_{HF}^{++}(36, 34) &= 16.11160 \text{ GHz} : J^{+++} = L + \frac{3}{2} \leftrightarrow J^{-++} = L + \frac{1}{2} \\ \nu_{HF}^{+-}(36, 34) &= 16.14341 \text{ GHz} : J^{++-} = L + \frac{1}{2} \leftrightarrow J^{-+-} = L - \frac{1}{2} \\ \nu_{HF}^{--}(36, 34) &= 11.12500 \text{ GHz} : J^{+--} = L - \frac{1}{2} \leftrightarrow J^{---} = L - \frac{3}{2} \\ \nu_{HF}^{-+}(36, 34) &= 11.15773 \text{ GHz} : J^{+-+} = L + \frac{1}{2} \leftrightarrow J^{-+-} = L - \frac{1}{2} \end{aligned} \quad (2)$$

The goal of this experiment is to measure the transitions between the SHF (SSHF) substates. From the measured frequency difference between two transitions it is possible to calculate the antiprotonic magnetic moment by comparison with the three-body QED calculations. The theoretical calculations have been developed by two different groups [5–7]. They used the same Hamiltonian for their calculations but the energy eigenvalues have been obtained using different variational methods. The hyperfine structures for $\bar{p}^3\text{He}^+$ and $\bar{p}^4\text{He}^+$ have been calculated most accurately by Korobov [8, 9].

3 Experimental method

The experimental technique is a three-step process, referred to as *laser-microwave-laser spectroscopy*. After antiprotonic helium is formed, the atoms in the hyperfine substates are in thermal equilibrium and all equally populated. Therefore, at first one has to create a population asymmetry between the SHF substates of the (n, l) state. This depopulation is induced by a laser which is applied for about 15–20 ns. The laser wavelength is fixed to the transition from one of the HF states of the radiative decay-dominated parent state to the Auger decay dominated daughter state, causing a population transfer between them. Subsequently, a microwave pulse is applied over a narrow frequency range around the transition frequency of the SHF ($\bar{p}^4\text{He}^+$) or SSHF ($\bar{p}^3\text{He}^+$) substates of the parent state. If it is on resonance with one of the transitions this will cause a population transfer between the substates and thus refilling of one of the previously depopulated states. A second laser is then fixed again to the same transition as before in order to measure the transferred population. The technique is displayed in Fig. 2.

There are several limitations to the choice of the measured state, such as laser capability or HF laser splitting. For $\bar{p}^4\text{He}^+$ the laser transition of the $(n, l) = (37, 35)$ state to $(n', l') = (38, 34)$ state had been chosen and successfully measured. This laser transition is easily stimulated. The splitting of the two laser transitions f^+ and f^- between the HF states of parent and daughter state (see Fig. 2) are large enough, $\Delta f = 1.27$ GHz compared to the Doppler broadening, $\Delta \nu_D = 420$ MHz, so that the hyperfine states can be resolved. This state is also highly populated compared to others in $\bar{p}^4\text{He}^+$ [10]. The new state that will be measured in $\bar{p}^3\text{He}^+$ is $(n, l) = (36, 34)$, which has similar characteristics to the $(n, l) = (37, 35)$ state of $\bar{p}^4\text{He}^+$.

The antiprotons for the experiment are provided at the AD (Antiproton Decelerator) at CERN, with a pulsed beam of $(1 - 3) \times 10^7$ antiprotons at an energy of 5.3 MeV, with a repetition rate of about 100 s. The antiproton pulse is stopped in a helium gas target which is cooled down to a temperature of 6K. The gas pressure is in the range of several hundred mbar. A signal is measured by detecting the annihilation decay products. The created pions go through two Cherenkov counters mounted around the target area and the resulting photons are detected by photomultipliers that are gated off during the initial $\bar{p}$ pulse arrival in order to record only the annihilations due to the metastable state depopulation.

The annihilation time spectrum shows a first sharp prompt peak after the $\bar{p}$ pulse which is caused by the majority of states that annihilate within picoseconds of formation due to the relatively short lived (~ 10 ns) daughter state merging into

Fig. 2 **a** Hyperfine structure of $\bar{p}^3\text{He}^+$. Wavy lines denote M1 transitions that correspond to a spin flip of the electron (HF transitions) which can be detected with our laser-microwave-laser method, while double arrows symbolise M1 transitions with spin flips of the antiproton or the helion, dashed lines refer to laser-induced E1 transitions. **b** Laser resonance profile for $\bar{p}^3\text{He}^+$, displaying the two sharp peaks for the laser transitions f^+ and f^- . There are four SHF lines, but two of them lie closer to each other (G^{+-} , G^{-+}) and thus only the G^{++} and G^{--} lines are visible (on the left peak)

an exponential tail due to the metastable states cascading slower towards the nucleus. This constitutes the background for the laser-induced annihilation signals and is called ADATS (Analog Delayed Annihilation Time Spectrum). The measured annihilation signal, i.e. the induced population transfer, is indicated by the ratio of the (laser-annihilation) peak area to the background. The second laser peak is mainly determined by the microwave induced transition between the hyperfine substates. It also depends on the time delay with respect to the first laser-induced annihilation peak and collisional relaxation effects. Both laser peaks can change in amplitude due to statistical fluctuations, $\bar{p}$ beam intensity and laser power. Therefore, the second laser-annihilation peak can be normalized to the first one. The two hyperfine transitions can now be obtained as distinct lines by displaying the peak-to-total of the second laser-annihilation signal normalized to the peak-to-total of the first laser-annihilation peak as a function of the microwave frequency.

4 New value for the antiproton magnetic moment

A precise measurement of the antiprotonic helium *hyperfine structure* (HFS) can be compared to three-body quantum electrodynamic (QED) calculations as a test of their predictions. If theory and experiment agree, a comparison between the measured transition frequencies and three body QED can be used to determine the antiproton spin magnetic moment $\mu_s^{\bar{p}}$. Compared to the proton magnetic moment it further provides a test of CPT invariance. The HFS of the $(n,l) = (37, 35)$ state of $\bar{p}^4\text{He}^+$ has now been thoroughly measured in terms of the energy eigenvalues.

Fig. 3 Latest experimental values for the single SHFS transition lines ν_{HF}^+ (left) and ν_{HF}^- (right) for the (37, 35) state of $\bar{p}^4\text{He}^+$ at different target pressures, compared to the theoretical values (from [11]). The red point shows the density-averaged experimental value (Pask 09 [13]), the triangles give the theoretical values (Korobov 01 [6], Korobov 09 [9]). The theoretical errors contain the numerical uncertainty and estimated higher order corrections

Recent experimental results [12, 13] have reduced the statistical error associated with the individual transitions $\nu_{\text{HF}}^\pm$ to a factor of 20 higher precision than that of initial calculations, see Fig. 3. This has motivated Korobov and Zhong to improve their calculations by adding $m\alpha^6$ order corrections to the electron spin – $\bar{p}$ orbital angular momentum term E1 [9]. Their new calculations for $\nu_{\text{HF}}^\pm$ are a factor 3 more precise than before and agree with the latest experimental results. The difference $\Delta\nu_{\text{HF}} = \nu_{\text{HF}}^- - \nu_{\text{HF}}^+$, which only depends on the $\bar{p}$ spin-orbit and spin-spin coefficients, has been resolved to a precision comparable to that of theory (33 kHz), a factor of 10 improvement over our first measurement [17]. A study of the collisional relaxation processes was commenced but could not be completed due to lack of time. As the values of the cross sections for spin-flip collisions is of interest to theory, further measurements of this quantity are still needed.

The most precise measurement of the proton to antiproton spin magnetic moment ratio to date is 0.3%. This is illustrated in comparison to previous measurements in Fig. 4. Our new measurements of $\nu_{\text{HF}}^\pm$ agree with the theoretical values within the calculation error of $\sim 3 \times 10^{-5} = 0.4$ MHz. It should be noted that the experimental errors are < 60 kHz. The difference between theory and experiment $\Delta_{\text{th-exp}}$ is at the ~ 400 kHz level, just about the size of the theoretical error. There is also good agreement between experiment and theory for $\Delta\nu_{\text{HF}}$, which is proportional to the spin magnetic moment of the antiproton. In 2009, the final measurement results of the (37,35) state of $\bar{p}^4\text{He}^+$ have been published [13]. By comparing the measured and calculated value of $\Delta\nu_{\text{HF}}$ and taking into account the sensitivity of $\Delta\nu_{\text{HF}}$ on $\mu_s^{\bar{p}}$, a new experimental value of the spin magnetic moment of the antiproton was obtained as

$$\mu_s^{\bar{p}} = -2.7862(83)\mu_N, \quad (3)$$

Fig. 4 Determination of the magnetic moment of the antiproton over time. Hu et al. [14], Roberts et al. [15], Kreissl et al. [16], Pask et al. [13] (from [11])

slightly better than the previously best measurement which so far dominates the combined value of the particle data group (PDG). Comparison to the proton magnetic moment gives

$$\frac{\mu_s^p - |\mu_s^{\bar{p}}|}{\mu_s^p} = (2.4 \pm 2.9) \times 10^{-3}. \quad (4)$$

Due to fluctuations of the $\bar{p}$ beam the precision achieved for the (37,35) state of $\bar{p}^4\text{He}^+$ cannot be further improved.

5 Antiprotonic ^3He

In 2009 the measurement of a new state has been started: the (n,l) = (36, 34) state of $\bar{p}^3\text{He}^+$. It was the first attempt to measure the hyperfine structure of antiprotonic ^3He . This exotic three-body system is more complex than antiprotonic ^4He . It contains only one neutron and two protons in contrast to ^4He with two neutrons and two protons. The coupling of the antiproton orbital momentum with the nuclear spin of the helium atom causes additional splitting of the hyperfine structure, resulting in eight substates instead of four. The interest in this particular system arises due to this more complex structure. Such a measurement would allow a more rigorous test of theory and further also address any systematic errors therein.

Simulations have been done on the hyperfine transitions to determine the expected signal to noise ratio, the RF power required to induce an electron spin flip and the influence of different line broadening effects. Calculations showed that the magnetic dipole moments are very similar to those for ^4He and therefore also the required power to induce an electron spin flip is in the same range. It is expected that also the collisional effects [18] are comparable to those for $\bar{p}^4\text{He}^+$. Theoretical calculations for $\bar{p}^3\text{He}^+$ are in progress.

Fig. 5 Drawing of the central part of the new setup, a cut through the cryostat (left). The microwave cavity for the 11 GHz transitions in antiprotonic ^3He mounted on the coldhead of the new, compressor-based cryostat (right)

6 New experimental setup

As described above, the antiprotons enter a small target, a cylindrical stainless steel cavity, filled with helium gas. The laser beam is sent into the target from the opposite side. The microwave pulse is provided by a vector network analyzer (VNA) and amplified by a travelling wave tube amplifier (TWTA). The signal is then forwarded to the microwave cavity through a waveguide system. This experiment with antiprotonic ^3He required an entirely new setup, refer therefore to Fig. 5. The transition frequencies between the super-hyperfine substates of antiprotonic ^3He are different from those in ^4He . Two new microwave cavities have to be designed in order to measure all four possible super-hyperfine transitions (see Fig. 2). The cavity for 11 GHz has already been tested and first measurements carried out. A new cryostat with compressor-based cooling system has been built. The microwave cavity is now cooled directly by mounting it on a coldhead. In comparison to the previous setup, now only the cavity is filled with the helium gas and by means of the coldhead cooled down to about 6 K. Liquid nitrogen and liquid helium are no longer needed to cool the cavity down. The cooling process is much faster than with the old system and it can be operated continuously, thus saving a lot of beamtime previously needed for refilling of the coolants.

The heart of our setup is the microwave cavity, a cylindrical resonator. There are a few fundamental requirements to be considered when building and testing this cavity. The resonance frequency of the cavity needs to be at the center between two of the four SSHF transitions in antiprotonic ^3He . There are four such transitions that can be induced using a microwave – two at about 11 GHz and two around 16 GHz. In order to measure the transitions which lie close to each other with one single cavity, a broad resonance is required to allow scanning over a broad frequency range of about 100 MHz at possibly equal power and magnetic field strengths. The central frequency of a cylindrical microwave cavity is defined by its dimensions – length

and radius. The broad resonance is achieved by overcoupling the waveguide to the cavity through an iris. The iris is a rectangular aperture in the cavity. Adjusting the dimensions allows the width (and as a consequence also the central frequency) of the resonance to be tuned. If we assume a closed cavity with no iris, one would obtain a sharp resonance at its central frequency and therefore only one of the transitions could be measured with the same cavity. By overcoupling the cavity to the waveguide system a sufficiently broad resonance can be obtained and thus both transitions can be measured with the same cavity at an equal power level. The only drawback is that considerably higher input power will be required. A microwave cavity is a very sensitive system and needs careful simulations and designing to fulfill the requirements for the experiment. The microwave part of the setup has been designed using the High Frequency Structure Simulator (HFSS) Software. It is essential to simulate the correct dimensions for the cavity in order to have the right frequency in resonance. Further, one has to make sure to exclude other modes resonating, which may interfere with the required field mode. There are several methods to investigate which modes exist and if the right mode is actually picked up. The TM₁₁₀ mode has been chosen since this is the lowest mode with the least number of nodes (zero) in the propagation direction of the antiproton beam. It is preferable to have a field as homogeneous as possible in axial direction of the cavity, so that the antiprotons entering the cavity experience the same field magnitude over the whole range.

7 Outlook

It is planned to study density dependence effects with $\bar{p}^3\text{He}^+$ as has been done also for $\bar{p}^4\text{He}^+$. The density dependence is found to be much smaller for the M1 transitions, the electron spin flip transitions induced by the microwave, than for the E1 transitions induced through laser stimulation. A theory group in Moscow predicts that nevertheless there is no such dependence, which should be proved with this study [19]. Antiprotonic ^4He will be investigated again for two reasons. On the one hand, we want to verify previous results with our new setup and thus exclude any problems with regards to the new hardware. Further, a study of collisional effects that could not be finished in 2009 due to lack of statistics shall be concluded in order to verify the theory on relaxation collisions.

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