Experminental Studies of Antiprotonic Helium


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Abstract

This talk describes the experimental studies of metastable antiprotonic helium “atomcules” \( \bar{p}\text{He}^+ \) (a neutral exotic atom consisting of a helium nucleus, an antiproton and an electron) performed at CERN-LEAR, and future plans for experiments at the forthcoming Antiproton Decelerator (AD) at CERN. Laser spectroscopy experiments are reviewed which led to the observation of a total of 13 resonant transitions of the antiproton in both \( \bar{p}\text{He}^+ \) and \( \bar{p}\text{He}^+ \), and revealed a hyperfine splitting in one transition. A level of precision has been reached where the most accurate 3-body calculations need to include QED effects like the Lamb-shift to come close to the experimental results.
1 Introduction

In the following the laser spectroscopy experiments performed by the PS205 collaboration [1] in 1991-1996 at the Low Energy Antiproton Ring (LEAR) of CERN will be overviewed. The latest results on the high-precision determination of transition energies at a 0.5 ppm level will be presented in a separate talk by H.A. Torii [2]. Unfortunately LEAR was shut down in 1996, but finally CERN decided to build a simplified antiproton machine, the AD (Antiproton Decelerator), where the experiments can continue from 1999. Those measurements planned by the ASACUSA [3] collaboration will also be described.

The metastable antiprotonic helium ”atomcules” were discovered by our group at an experiment at KEK, Japan, in 1991 [4] where it was found that about 3% of $\bar{p}$ stopped in liquid helium survive with an average lifetime of about 3 $\mu$s, while the remaining 97% are immediately (i.e. within $< 10^{-12}$ s) captured by the nucleus (cf. Fig. 1). Immediately a new collaboration named PS205 was founded to investigate this surprising phenomenon at LEAR of CERN, were the superb antiproton beam allowed for the stopping of $\bar{p}$ even in low-density gaseous helium targets. In the beginning, delayed annihilation time spectra (DATS) were taken in various phases of helium, from low-temperature gas to liquid and solid He. The results [5, 6, 7] (cf. Fig. 2) showed that the average lifetime $T_{av}$ of $\bar{p}$ in He is very insensitive to the density of the surrounding helium atoms. Similarly, $T_{av}$ is affected only slightly if other noblegases are added in concentration up to $\sim 10\%$ (except in the case of Xe) [8], while the metastability is almost completely destroyed by adding molecular gases at the $\sim 100$ ppm level [5, 6, 8]. Similar results were reported by the OBELIX collaboration [9, 11, 10], although there exists a discrepancy in the observed quenching cross sections for Ne and Ar admixtures.

At that time the most promising model to describe the observed metastability was the one developed earlier by Condo [12] and Russell [13], which attributes the metastability to the formation of highly excited “circular” states ($n \sim L - 1$ with $n =$ principal quantum number and $L =$ angular quantum number of the $\bar{p}$) around the initial capture state $n_0 = \sqrt{M*/m}$ of the antiproton in a neutral exotic atom $\bar{p}$-$e^-$. $+$He$^{2+} \equiv \bar{p}$He$^+$ ($M*$ being the reduced mass of the $\bar{p}$He$^+$ system, and $m$ the electron mass). Since this unusual system has the properties of both an atom and a molecule we often refer to it as an ”atomcule” [5]. Because for circular states the level spacing in $\bar{p}$He$^+$ is about 2 eV, $\bar{p}$ captured in states of lower $L$ can more easily liberate the 24.6 eV needed to ionize the electron and undergo an Auger transition with a small step in $\Delta L$. Radiative transition rates are rather small due to the small energy difference between adjacent levels. More recent calculations of Yamazaki and Ohtsuki [14] and Shimamura [15] for antiprotonic helium atomcules as well as our measurements yielded level lifetimes of about 1 $\mu$s for circular states.

The insensitivity to the surrounding helium atoms can be understood because of the presence of the electron in the atomcule. It’s existence removes the degeneracy of $L$-levels of the same $n$, thus suppressing Stark mixing of $L$ states. The neutrality prevents the atomcule to be destroyed by external Stark effect via po-
Annihilation Time (µs) counts / 200 ns

prompt trapping fraction: ≈ 3 %
average lifetime: ≈ 3 µs

delayed annihilation of pbar in liquid helium, KEK 1991

delayed

Figure 1: Delayed Annihilation Time Spectrum (DATS) of p stopped in liquid helium as discovered at KEK[4]

larizing the environment, and the Pauli principle shields it from close encounters with other helium atoms. An isotope effect found between p³He⁺ and p⁴He⁺ [16] is also in agreement with the Condo-Russell model [14].

With the availability of theoretical calculations of the antiproton energy levels inside the atomcule [14, 15, 17, 18, 19], a test of the structure of the pHe⁺ system as predicted by the Condo-Russell model using laser spectroscopy became feasible.

We developed a spectroscopy technique [20, 21] which will be described in section 2.1. It makes use of the results of calculations of the Auger transition rates by Ohtsuki [22] who showed that they become bigger than the radiative rates for levels which can undergo a transition with “multi-polarity” ΔL ≤ 3 to the next lower-lying state of ionized pHe²⁺. Therefore the (n, L)-plane is divided into a metastable (τ ~ 1 µs, solid lines in Figure 3) and a short-lived part (τ ≤ 10 ns, wavy lines in Figure 3). The p initially captured in high-(n, L) states perform transitions along cascades of constant vibrational quantum number v = n − L − 1 [14, 15] until they reach a short-lived state from where they undergo an Auger transition which ionizes the atomcule. The charged pHe²⁺ in the dense surrounding of liquid helium is then immediately destroyed by external Stark effect which mixes levels of different angular momentum and thus brings the p close to the nucleus, where it annihilates instantly with a nucleon.

Figure 2: DATS of $\overline{p}$ stopped in various phases of helium showing the insensitivity of the delayed component to the density of the surrounding medium (a)-(d) and admixtures of noble gases (e), while small admixtures of hydrogen molecules have a strong effect on the metastability (f). The prompt peak has been removed during the analysis.

V.I. Korobov [26] became available which agreed with our experimental results at the 50 ppm level and therefore boosted the speed of searching for new transitions and so in 1995 a total of three new transitions in $\overline{p}^4\text{He}^+$ and two in $\overline{p}^3\text{He}^+$ could be observed [27, 28, 29]. Two of the transitions of type $\Delta \nu = 2$ (called “unfavoured” because of the one order of magnitude smaller dipole transition moment as compared to $\Delta \nu = 0$ ones) were found using a novel method of pulsed extraction from LEAR [29, 30]. All together, these findings established the correctness of the Condo-Russell model as an explanation of the structure of the $\overline{p}\text{He}^+$ atomcule beyond any doubts.

The laser spectroscopy experiments can be divided into two subjects, one dealing with the structure of the atomcule and another one with its formation and decay, i.e. its interaction with other atoms and molecules. The latter constitutes a very interesting subject for atomic collision and chemical physics research, since by laser-tagging state-dependent information on the change of level lifetimes through the interaction of the atomcule with other helium atoms [31] as well as hydrogen [32, 33] and oxygen [34] molecules can be obtained. In addition, making use of the possibility to influence the lifetime of certain levels [31], we were able to extend the region of laser spectroscopy to pairs of normally metastable states [35]. But since these topics are unrelated to the subject of this workshop, they will not be treated in this paper.

In the following the laser spectroscopy technique will be described, and the
Figure 3: The level scheme of large–$(n, L)$ states of the $\bar{p}$He$^+$ atomcule. Solid lines indicate metastable levels, dashed lines Auger-dominated short-lived ones. The arrows symbolize the preferred transitions of the $\bar{p}$ along cascades with $\Delta v = \Delta(n - L - 1) = 0$. The experimentally observed transitions are denoted by bold arrows.

results on the determination of transition energies down to a 2-3 ppm level will be presented. Newer results on the improvement of the experimental precision for two resonance lines can be found in the talk by H.A. Torii [2, 36]. The observation of a hyperfine splitting in one transition [37] will be discussed, and planned experiments at the forthcoming AD machine at CERN will be reviewed.

2 Laser Spectroscopy of $\bar{p}$He$^+$ atomcules

2.1 Principle

The idea to perform laser spectroscopy of the antiproton levels in $\bar{p}$He$^+$ came from the wish to confirm the structure of this 3-body system and to verify that the antiproton occupies levels with quantum numbers around $(n, L) \sim 38$. Our laser spectroscopy technique [20, 21] made use of the fact as described above that at the end of each cascade with constant vibrational quantum number $v$ there exists a pair of metastable and short-lived states. If the $\bar{p}$ is resonantly deexcited by a laser pulse, the atomcule will ionize via an Auger transition and will immediately be destroyed by external Stark effect in the dense medium. The signal of the resonance condition will then be a sharp spike appearing in the annihilation time spectrum at the time of the laser pulse, which has a width determined (roughly) by the Auger lifetime of the daughter state.
Figure 4: Experimental setup for laser spectroscopy. The cylindrical cryostat in the center contains the target gas chamber of ~ 6 cm diameter and 18 cm length, where He gas was kept at pressures of about 0.6–1 bar and temperatures of 6–10 K. The antiprotons entered through a 0.4 mm thick stainless steel window. The laser beam was collinear to the particle beam, entering through a quartz window on the downstream side of the cylindrical chamber. The cryostat was surrounded by 7 lead-scintillator sandwich counters which detected charged and neutral pions from the $\bar{p}$ annihilation with an overall efficiency of >99.5% per annihilation.

2.2 Experimental setup

The experimental setup is described in great detail in another publication [21]. Antiprotons were stopped in a low-temperature helium gas sample (typically 6-10 K and 0.6-1 bar pressure) (see Fig. 4). The time was measured between a $\bar{p}$ entering the target (defined by a scintillation counter) and its annihilation into several charged and neutral pions (detected by seven lead-scintillation sandwich counters). The sandwich counters were needed to have a very large detection efficiency for each annihilation including those which produce exclusively neutral pions in order to avoid unnecessary triggers for the lasers.

The experiment was performed both in slow (continuous) and fast (pulsed) extraction from LEAR. For slow extraction, $\bar{p}$ arrived at an average rate of $10^4 \bar{p}/s$. Each time a $\bar{p}$ entered the target and no prompt annihilation was observed
within 100 ns, the lasers were fired and the one metastable atom present in the target was deexcited. In fast extraction a pulse of $10^8 - 10^9$ of 150 - 200 ns length was injected into the target, where 3% formed an ensemble of metastable atoms similar to a radioactive source. In this case the time spectrum was obtained in an analogue way by recording the output of a gated photomultiplier by a digital storage oscilloscope [30, 29].

The laser system consisted of two sets of commercial dye lasers (Lambda Physic LPD3002) pumped by Excimer lasers (Lambda Physik LPX240i) which provided 30 ns long pulses of $\sim 10$ mJ power with a maximum repetition rate of 400 Hz. Since theoretical calculations available at the start of our laser spectroscopy experiments differed by as much as $10^{-3}$ [14, 15, 17, 18, 19], the lasers were optimized for large bandwidth (6-10 GHz, $\sim 10^{-7}$).

2.3 Observed resonance lines and comparison to theoretical calculations

Due to the large theoretical uncertainty and the relative small bandwidth of the lasers, we could observe the first resonant transition in 1993 [23] (cf. Fig. 5) only after scanning for 5 days. The same way we found a second resonance in 1994.

Figure 5: Left: DATS taken with different laser wavelengths. As the wavelength is scanned through 597.259 nm, a sharp spike appears in the time spectrum which later disappears at larger wavelengths. Upper right: blow-up of the laser spike in the time spectrum showing a steep increase and an exponential decay which partly reflects the Auger lifetime of the daughter state. Lower right: resonance strength (integral below the peak normalized to the total delayed annihilations) vs. wavelength.

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Then a new calculation of Korobov became available [26] which agreed with our values at the 50 ppm level. Therefore, in 1995 we could find 5 new transitions in 1995 [27, 28, 29] and 6 more in 1996, one in $^3$He [38] and 5 by making use of state-dependent quenching by hydrogen admixture [35]. By comparing the measured wavelengths to Korobov's calculations, we could assign both principal and angular quantum numbers to all transitions, thus proving for the first time that $\overline{\rho}$ are indeed captured into orbits around $n_0 \sim \sqrt{M^*/m}$.

Subsequently Korobov together with Bakalov refined his calculations taking into account relativistic corrections to the motion of the electron [39, 40]. Fig.6 compares all measured transition wavelengths to the result of this calculations showing an agreement of 2-3 ppm. Recently, other authors published calculations of similar accuracy [41, 42, 43, 44, 45], some of them already calculating the Lamb shift contribution. These improvements will be discussed in the talk by H.A. Torii [2] together with new experimental results where we could improve our accuracy for two of the lines by one order of magnitude. This was possible since $i)$ we observed a shift of the resonance line center with pressure and extrapolated it back to zero density and $ii)$ we could improve the calibration of our wavelength measuring device. The experimental accuracy of 0.5 ppm is now getting close to

![Figure 6: Relative deviation of theoretical results by Korobov [26, 39] from experimental values. The error bars shown are the experimental ones. Most experimental values have been obtained at our “standard conditions” of 6.1 K and 0.6 mbar.](image-url)
3 Observation of a hyperfine splitting in an unfavoured transition

The levels in a $\bar{p}$He$^+$ atomcule are split due to the magnetic interaction of its constituents. Because the $\bar{p}$ is in a large angular-momentum state ($L \approx 33\ldots35$), each level is first split into a doublet due to the interaction of the $\bar{p}$ angular momentum $\vec{L}$ and the electron spin $\vec{S}_e$ (cf upper part of Fig. 8). Since this splitting originates from the interaction of particles of a different kind, we refer to it as hyperfine (HF) splitting. Each of the doublet states is furthermore split into two states due to the interaction of the antiproton spin $\vec{S}_{\bar{p}}$ with the other magnetic moments. This splitting which we call super-hyperfine (SHF) splitting is much smaller than the HFS.

Laser transitions between two quadruplets follow predominantly the selection rules $\Delta S_e = \Delta S_{\bar{p}} = 0$ due to the large angular momentum $L$ of the $\bar{p}$. This means that, although the HF and SHF splittings are large, the splittings in the laser frequencies, which are the difference of the splittings of parent and daughter state, are very small. Theoretical predictions available in 1996 showed [47, 48, 49] that the biggest splitting occurs in unfavoured transitions. We therefore performed a scan of the previously observed transition $(n, L) = (37, 35) \rightarrow (38, 34)$ at $\lambda = 726.1$ nm [29] with our laser system tuned to the minimum possible bandwidth of $\sim 1.2$ nm.

![Figure 7: Observed hyperfine splitting in the $(n, L) = (37, 35) \rightarrow (38, 34)$ transition of antiprotonic helium.](image)
GHz. Indeed, we could observe a doublet structure (cf Fig.7) with a separation of \( \Delta \nu_{HF} = 1.70 \pm 0.05 \text{ GHz} \) [37], in agreement with the latest calculations of Bakalov and Korobov [50, 51]. This consists of the first observation of such an unusual hyperfine splitting in a three-body system. Future experiments planned at the CERN-AD will be described in the next section.

4 Future experiments at CERN-AD

After the approval of the AD machine at CERN, a new collaboration named ASACUSA (Atomic Collisions And Spectroscopy Using Cold Antiprotons) [3] was formed by members of groups previously working on atomic collision and spectroscopy at LEAR, among them members of the PS205 collaboration. In the first year of the AD (1999), the ASACUSA collaboration will continue the experiments on antiprotonic helium atomcules.

The general program includes the extension of the atomic collision program measuring state-dependent quenching cross sections in collisions of atomcules with other atoms and molecules, the extension and improvement of the experimental accuracy for the transition energies for all observed transitions [2], and the search for so far undiscovered transitions. One of the major subjects will be the direct measurement of the hyperfine splitting of the antiproton levels, which will be described in more detail in the following paragraph.

4.1 Measurement of the atomcule hyperfine structure

The \( \overline{p}\text{He}^+ \) atomcule has three angular momenta; \( L \): orbital angular momentum (mainly carried by \( \overline{p} \)), \( S_p \): \( \overline{p} \) spin and \( S_e \): electron spin. Let us define the angular momentum coupling as follows:

\[
\begin{align*}
\vec{F} &= \vec{L} + \vec{S_e} & (1) \\
\vec{j} &= \vec{L} + \vec{S_p} & (2) \\
\vec{J} &= \vec{F} + \vec{S_p} = \vec{j} + \vec{S_e} = \vec{L} + \vec{S_p} + \vec{S_e} & (3)
\end{align*}
\]

As mentioned above, the dominant effect is a doublet \( (F^+ = L + 1/2 \) and \( F^- = L - 1/2 \), separated by \( \nu_{HF} \) ) caused by the interaction of the spin-averaged \( \overline{p} \) magnetic moment (due to the large \( L \) ) with the electron spin. This splitting is called Hyperfine (HF) Structure. The \( \overline{p} \) spin causes an additional smaller splitting for each of the HF state, which is called here Super Hyperfine (SHF) Structure.

The HF and SHF structure has been calculated by Bakalov and Korobov [48, 50, 51] using the best three-body wavefunctions of Korobov [39]. The level and transition scheme involving both HF and SHF is shown in the upper part of Fig. 8. The HF and SHF energies are presented in terms of the angular momentum operators as
\[ \delta E = E_1(\vec{L} \cdot \vec{S}_e) + E_2(\vec{L} \cdot \vec{S}_p) + E_3(\vec{S}_e \cdot \vec{S}_p) + E_4\{2L(L+1)(\vec{S}_e \cdot \vec{S}_p) - 6(\vec{L} \cdot \vec{S}_e) \cdot (\vec{L} \cdot \vec{S}_p)\} \] (4)

The first term gives a dominant HF splitting.

The lower and the upper states of a HF doublet have \( F^+ \) and \( F^- \), respectively. Their level order is opposite to that of the hydrogen atom, because of the opposite

\[ (n',L') \]
\[ (n,L) \]

\[ \nu_{HF}' = L' + 1/2 \]
\[ \nu_{HF} = L - 1/2 \]

\[ \nu_{HF} = L - 1 \]
\[ \nu_{HF} = L + 1 \]

\[ \nu_{HF} \]

\[ \nu_{HF} \]

\[ \nu_{HF} \]

\[ \nu_{MW} = \nu_{HF} \pm \nu_{HF} \]

\[ \nu_{MW} = \nu_{HF} \]

\[ \nu_{MW} = \nu_{HF} \]

\[ \nu_{MW} = \nu_{HF} \]

Figure 8: Two-laser microwave triple resonance experiment explained at the example of the already observed \((n, L) = (37, 35) \rightarrow (38, 34)\) transition. Top: laser, microwave, and RF transitions in \(^{3}P\)He\(^{+}\). Bottom left: Simulated delayed annihilation time spectra of the laser/microwave triple resonance method. Bottom right: Simulated laser and microwave resonance profile.
sign of the “nuclear magnetic moment”. The SHF structure is a combined effect of i) (the second term) the one-body spin-orbit interaction (called historically Fine Structure, but small in the present case, because of the very large \((n, L)\)), ii) (the third term) the contact term of the \(\vec{S}_p - \vec{S}_e\) interaction and iii) (the fourth term) the tensor term of the \(\vec{S}_p - \vec{S}_e\) interaction. According to the calculation, the contact and the tensor terms almost cancel and the SHF splitting is nearly equal to the one-body spin-orbit splitting as given by the second term. Thus, its level order (the \(j^- = L - 1/2\) level is lower than the \(j^+ = L + 1/2\) level) is retained here; the \(F^+ = L + 1/2\) member is split into lower \(J^{+-} = F^+ - 1/2 = L\) and upper \(J^{++} = F^+ + 1/2 = L + 1\) submembers, and the \(F^- = L - 1/2\) member is split into lower \(J^{--} = F^- - 1/2 = L - 1\) and upper \(J^{+-} = F^- + 1/2 = L\) submembers, as shown in Fig. 9.

As described in the previous section, a laser spectroscopy measurement should reveal a quadruplet structure of each transition line, where the distance between the sub-lines is equal to the difference in splittings of the parent and daughter states. But from theoretical calculations \([50, 51]\) it follows that the splitting arising from the SHF splitting is too small \((\approx 10 \ldots 50 \text{ MHz})\) to be resolved in our experimental conditions where the Doppler broadening at 10 K already amounts to \(\sim 400 \text{ MHz}\). The doublet due to the HF splitting, however, is in the order of \(1.6 \ldots 1.9 \text{ GHz}\) as already observed and can therefore be more clearly separated.
with a laser of bandwidth \( \leq 1 \) GHz. Nevertheless such an experiment yields only
the difference of two level splittings with rather limited accuracy.

More promising is to directly measure the level splitting using a microwave
technique. But in order to obtain a clear signal, first a population asymmetry
has to be induced between the sub-states. This can be done using a two-laser
microwave triple resonance technique as we proposed to do it at the AD [3].

The method is explained in Fig.8. We assume that a laser can be tuned to
one of the sub-lines \( f_+ \) or \( f_- \) of the laser doublet (cf. Fig.8a). Applying a laser
pulse of frequency \( f_+ \) at time \( t_1 \) will therefore reduce the population of the level
\( F^+ = L + 1/2 \) with a certain efficiency, while the level \( F^- = L - 1/2 \) will be
less or not at all affected, depending on the achievable laser bandwidth. Applying
subsequently a second pulse of frequency \( f_- \) at time \( t_2 \) will show the population
of \( F^- \) which is only affected by the decay and feeding from upper states (Fig.8A).
A second pulse of the same frequency \( f_+ \) at time \( t_2 \), however, will show only the
remaining population which was not completely destroyed by the first pulse, plus
any population due to feeding from upper states (Fig.8B).

If in between the two laser pulses a microwave field was applied on resonance,
a part of the population of the \( F^- \) level can be transferred to the \( F^+ \) level, and the
second pulse of frequency \( f_+ \) will detect an increase in population as compared to
the off-resonance case (Fig.8C).

Within a state quadruplet there exist two possible magnetic transitions denoted
\( \nu_{HF} \) and \( \nu_{HF}^+ \). Defining the intensity ratio of the second peaks in Figs.8a) and b)
by

\[
R^{++}(\nu_{MW}) = \frac{I_2(f_1 = f^+, f_2 = f^+)}{I_2(f_1 = f^+, f_2 = f^-)} \tag{5}
\]

we get a resonance curve for the microwave transition as shown in (Fig.8b)
for the \((n, L) = (37, 35)\) state. It shows two peaks with an central frequency of
12.91 GHz, separated by the difference \( \nu_{SHF}^+ - \nu_{SHF}^- \), here 28 MHz as predicted
by Bakalov and Korobov [50, 51].

### 4.2 Significance of atomcule hyperfine studies

The \( \overline{\text{pHe}}^+ \) atomcule is an extremely exotic yet fundamental three-body system,
composed of a \( \overline{\text{p}} \), an \( e^- \) and the nucleus. With the advent of both experimental
and theoretical progress of \( \overline{\text{pHe}}^+ \) spectroscopy the state of art is now matured
enough to handle the hyperfine/superhyperfine structure of this atomcule to high
precision. In the following we discuss briefly what we can learn from the proposed
studies.

#### 4.2.1 Hyperfine structure (\( \nu_{HF} \))

The ultimate precision is limited by the natural width of the metastable state (order
of 0.2 MHz) and its uncertainty of the microwave resonance can be reduced to 0.1
kHz or so on the 12.9 GHz microwave transition frequency. Thus, we expect a relative precision of $10^{-8}$. The theoretical values calculated with the best Korobov wavefunctions have a precision of $10^{-4}$ which can be increased to $10^{-5}$ taking into account leading order radiative corrections [50, 51]. The theory can be tested to such high precision. A disagreement between theory and experiment, if revealed, will give insight into the three-body wavefunctions, the orbital magnetic moment of $\bar{\mathfrak{p}}$ and QED corrections.

4.2.2 Superhyperfine structure ($\nu_{\text{SHF}}^-$ and $\nu_{\text{SHF}}^+$)

The two SHF frequencies jointly provide well separated information on the one-body spin-orbit term and the spin-spin term. If a doublet structure is observed in the laser/microwave triple resonance and its splitting is indeed small, as predicted ($\sim 28$ MHz in the case of the (37,35) state), this will indicate that the one-body spin-orbit term is dominant, since the $S_p \cdot S_e$ term should contribute to the upper and the lower doublets in opposite directions.

The spin-orbit splitting of leptonic particles is well known. For hadronic particles, which are subject to enormous structural corrections ($\mu(p)/\mu_N = 2.79 = 1 + a_p$), the spin-orbit term is proportional to

$$(1 + 2a_p)s \cdot \vec{l}. \quad (6)$$

This large correction has not even been tested for a protonic system, because of the absence of a “protonic atom” with a large proton orbital angular momentum. For $\bar{\mathfrak{p}}$, in contrast, this term can be measured from spin-orbit doublets of antiprotonic atoms. The best known case is from the fine structure of the $n = 11 \rightarrow 10$ X ray transition of $\bar{\mathfrak{p}}$ Pb [52], in which this term was tested to the precision of $3 \times 10^{-3}$. The $\nu_{\text{SHF}}^-$ and $\nu_{\text{SHF}}^+$ will provide a more stringent test of this term (or equivalently, the magnetic moment of $\bar{\mathfrak{p}}$).

5 Summary and Outlook

The study of antiprotonic helium atomcules $\mathfrak{p}$He$^+$ has evolved over the years from the initial curiosity-oriented research to a “high-precision” oriented spectroscopy field. The laser spectroscopy method developed by our group has for the first time provided experimental evidence for the assumption that an exotic particle is initially captured into orbits with principal quantum number $n_0 \sim \sqrt{M^*/m}$ as it was commonly accepted. With the step-by-step improvement in experimental and theoretical precision, this highly unusual three-body system consisting of an helium nucleus, an electron and an antiproton has now reached a level where QED corrections like the Lamb shift have to be calculated to explain the measured transition energies. If both theoretical and experimental accuracy can be improved in the future, the atomcule may surpass the ordinary helium atom as the best calculated and experimentally verified three-body system, allowing for stringent tests on the accuracy of three-body calculations.
By making these comparisons we can also extract information on intrinsic properties of the antiproton. As described in the talk of H.A. Torii, already at the current level of precision we could set a new limit on the proton to antiproton charge ratio which constitutes a test of CPT invariance. The also very unusual hyperfine structure may provide except of tests of the calculation technique information on the antiproton magnetic moment, another property related to CPT invariance.

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