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Antiprotonic Helium Atoms

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Abstract

Metastable antiprotonic helium atoms $^{3,4}He\bar{p}e$ have been discovered recently in experiments of the delayed annihilation of antiprotons in helium media. These exotic atoms survive for an enormous time (about tens of microseconds) and carry the extremely large total angular momentum $L \sim 30-40$. The theoretical treatment of the intrinsic properties of antiprotonic helium atoms, their formation and collisions with atoms and molecules is discussed.

1 Introduction

Metastable antiprotonic helium atoms ${}^{3,4}He\bar{p}e$ have been discovered recently in experiments on the delayed annihilation of antiprotons in helium media [1–3]. A few percents of antiprotons are captured in these exotic systems, which survive for an enormous time (about tens of microseconds in comparison with the mean lifetime of antiprotons in media $\sim 10^{-12}s$) and carry the extremely large total angular momentum $L \sim 30 - 40$. Analogous long-lived systems were observed in experiments with negative kaons [4] and pions [5]. This new class of three-body systems was first predicted in [6] and theoretically studied in [7]. As far as the experimental data concern mainly the antiprotonic helium atom, only this system is considered in this report. One can mention that described theoretical considerations can be easily applied also to other hadronic helium atoms.

The observation of the resonant laser-induced annihilation [8,9] has initiated thorough investigations of these unusual systems. Initial populations, level lifetimes and very precise values of the transition energies (with the relative accuracy $< 10^{-5}$) have been obtained in these experiments.

The antiprotonic helium can be considered as a usual helium atom with one electron replaced by an antiproton. A large angular momentum $L \sim (M/m_e)^{1/2}$ ($M-\bar{p}$–nucleus reduced mass) provides that the antiproton-nucleus and electron-nucleus distances are approximately equal. Besides, this system can be considered as exotic diatomic molecule, where one nucleus has charge -1.

Main reasons for the enormous lifetime of antiprotonic helium atoms are as follows. The annihilation of an antiproton is inhibited due to the extremely large total angular momentum $L \sim 35$. The Auger decay is inhibited due to sufficiently large values ($l_e \geq 4$) of the angular momentum of an outgoing electron. Usual mechanism of the de-excitation by the Stark mixing is not appropriate to the three-body system due to the lack of degeneracy. The collisional de-excitation by surrounding He atoms is suppressed due to the screening of antiproton by the electron in an antiprotonic helium. The only remaining de-excitation mechanism is multistep radiative transitions, whose rates are of order μs^{-1}.

For clear understanding of the antiproton fate in the helium medium one needs to study the slowing down and capture of antiprotons, intrinsic properties of antiprotonic helium atoms, their decay processes and interactions with surrounding atoms and molecules. The purpose of this report is to present the results of existing theoretical calculations on antiprotonic helium atoms and related topics with the reference to the modern experimental situation.

2 Energy levels

Main problems in the calculation of energy levels arise from very large values of the total angular momentum $L \sim 30 - 40$ of antiprotonic helium atoms and instability of these systems. However, very small decay rates allow one to regard in calculations states of these systems as true bound states.

The first calculations of energy levels were made in the pioneering Russel papers [7]. Using a simple two-parameter variational wave function, energy levels were calculated with the relative accuracy about 3 percents. The Born-Oppenheimer approximation will be quite reliable in solving this problem due to very small mass ratios $m_e/m_{\bar{p}}, m_e/m_{He}$ and the next step has been made in the framework of this approach [10]. Only ground states were considered in this paper and more systematic study of antiprotonic helium eigen-energies within the same approach was carried out in papers [11,12] after the discovery of the delayed antiproton annihilation [1]. The relative accuracy of eigen-energies obtained in these calculations can be estimated as 10^{-4}.

The configuration interaction calculation [13] provides a comparable accuracy of eigen-energies without the reference to the small mass ratio. Systematic variational calculations [14], with simple trial functions of the form

$$\chi_{nml\lambda i}^{LM}(\mathbf{r},\mathbf{r}_1) = \mathcal{Y}_{l\lambda}^{LM}(\hat{\mathbf{r}},\hat{\mathbf{r}}_1) r^{l+i} r_1^{\lambda} exp(-a_n r - b_m r_1), \tag{1}$$

where $\mathbf{r}, \mathbf{r_1}$ are the electron-nucleus and antiproton-nucleus radius-vectors, also provide accuracy of the same order of magnitude. Very recently, V. I. Korobov has obtained more precise spectra of an antiprotonic helium, using the correlated trial functions in variational calculations [15].

By using the method of laser-induced resonant annihilation, two transition wavelengths $597.259 \pm 0.002 nm$ [8] and $470.724 \pm 0.002 nm$ [9] were measured in the $^4He\bar{p}e$ system and assigned to the transitions $(36, 4 \to 35, 4)$ and $(35, 3 \to 34, 3)$, respectively. The most important for proving the existence of antiprotonic helium atoms is to compare experimental and theoretical transition wavelengths given in Table 1. Here and below in this report the L, N notation of states, where L is the total angular momentum and N enumerates the states of the same L value, will be used.

Table 1. Experimental and theoretical transition wavelengths (nm) of the $^4He\bar{p}e$ system.

Assignment	Experim.	[16]	[11]	[14]	[15]
$35, 4 \to 34, 4$	597.259	597.341	598.010	597.544	597.229
$34, 3 \to 33, 3$	470.724	470.594	471.351	470.871	470.705

While the agreement of experimental and theoretical transition wavelengths approves the formation of antiprotonic helium atoms unambiguously, it is worthwhile to mention a possible ambiguity in the assignment of the 470.724nm transition. In fact, the calculated wavelength of the transition $(35, 2 \to 34, 2)$ is also very close to the experimental value.

In conclusion, a more precise description of energy spectra requires to take into account the effect of relativistic and QED corrections, spin-dependent interactions and the coupling with continuous spectrum.

3 Radiative transitions

Due to large lifetimes of metastable states against Auger decay and collisional de-excitation the radiative transitions become most important in the description of the system. As far as only dipole transitions are significant, the total angular momentum changes by unity in each transition. Thus, the system looses the angular momentum and energy step-by-step and finally reaches the state with large Auger decay rate. As a result, the total lifetime is determined by the number of radiative transitions necessary to reach this state and rates of each transition.

The dipole transition rates were calculated in papers [11,13,14,17], whose results are fairly close to each other. It was found that the most probable are transitions between states of the same N, i. e. the excitation number is approximately conserved in the radiative transitions. At the same time, the rates of transitions between states with different N are smaller at least by 1–2 orders of magnitude. Thus, radiative cascades in an antiprotonic helium proceed almost independently along the chains of states of fixed N.

Up to now, lifetimes of the states $(L, N) = (35, 4)$ and $(34, 3)$ of ${}^4He\bar{p}e$ system are determined experimentally by the method of resonant laser–induced annihilation [9,18]. Table 2 contains the experimental decay rates and theoretical radiative transition rates of these states. The difference of experimental and theoretical values is not still understood and may be caused by additional nonradiative decay channels.

Table 2. Experimental decay rate and theoretical radiative transition rates $(10^6 s^{-1})$ for two states of the ${}^4He\bar{p}e$ system.

L, N	Experiment	[17]	[11]	[14]
$35, 4$	0.72	0.614	0.619	0.597
$34, 3$	1.18	0.734	0.754	0.713

One can conclude that the existing calculations of radiative transitions are reasonable accuracy and a detailed consideration of other decay processes is needed.

4 Auger decay

The main feature of the Auger decay rates of antiprotonic helium atoms is their essential dependence on the multipolarity, i. e. the angular momentum of the outgoing electron l_e. This feature was supposed already in [6] and any simple estimate gives the Auger transition rate of order $10^5 s^{-1}$ for the multipolarity $l_e = 4$ and $10^8 s^{-1}$ for $l_e = 3$. This important result was initially obtained in [7]. Bearing in mind the radiative transition rates of order $(10^6 s^{-1})$, one can consider antiprotonic helium states to be metastable due to the multipolarity of the Auger decay $l_e \geq 4$. Calculation of eigen-energies unambiguously determines multipolarities of the Auger decay and it was performed firstly in [7] and more exactly in subsequent papers [10,11,13,14].

Up to now the only progress in this direction is due to calculations of the Auger decay rates of the ${}^4He\bar{p}e$ system [16,17]. In these calculations, an increase of the multipolarity from $l_e = 3$ to $l_e = 4$ as a rule gives a decrease of the Auger rate by three orders of magnitude. Besides, for some states the calculated Auger rates are much smaller than the typical values prescribed by the multipolarity. This interesting peculiarity is a result of the interference of different parts of the initial and final state wave functions.

It is worthwhile to mention that these results are based on the approximation of the continuous spectrum final state wave function. Namely, the effective two–body model was used to describe the interaction of the outgoing electron and the hydrogenlike $\bar{p}He^{++}$ system.

As it was mentioned in the preceding section, the experimental data call for the intensive theoretical study of decay processes and precise few–body calculations are desirable for understanding the cascade processes in an antiprotonic helium.

5 Energy levels' splitting and relativistic corrections

As it was discussed above, the precise measurement of transition energies of antiprotonic helium atoms in recent experiments on the laser-induced resonant annihilation invokes the calculations of comparable accuracy. For this reason, relativistic corrections of order α^2 (in a.u.) to the pure Coulomb interaction should be taken into account in the precise calculations of energy spectra of antiprotonic helium atoms. Since the precision of experiments can be improved significantly, also QED corrections to energies of higher orders on α will be calculated. Precise calculations and measurements of the energy spectra can be also used for the determining the antiproton properties, e.g. the magnetic moment. Experimentally, the most simple is the measurement of the energy-level splitting due to the spin-dependent part of the relativistic interaction.

Recently, the energy-level splitting of antiprotonic helium atoms has been calculated with the wave functions [14]. The details of this calculation and analysis of the level structure will be presented in [19]. Short results of this calculation are given below.

The splitting of levels arise due to the spin-dependent part of the Breit interaction in each pair of particles in antiprotonic helium atoms. Since the magnetic moments and velocities of particles scale inversely proportional to the particle mass and very small ratios $m_e/m_{He}, m_e/m_{\bar{p}}$, the largest contribution to the energy splitting comes from the interaction with the electron spin. This part of relativistic interaction can be written as follows:

$$H_s = \alpha^2 \sum_{i=\bar{p},He} \frac{Z_i}{r_{ei}^3} \mathbf{s}_e \cdot \mathbf{r}_{ei} \times (\tfrac{1}{2}\mathbf{v}_e - \mathbf{v}_i), \tag{2}$$

where α is the fine structure constant, $\mathbf{r}_i, \mathbf{v}_i, \mathbf{s}_i, \mathbf{Z}_i$ are the radius-vector, velocity, spin and charge of particle i, $\mathbf{r}_{ei} = \mathbf{r}_e - \mathbf{r}_i$.
This interaction conserves the sum $\mathbf{j} = \mathbf{L} + \mathbf{s_e}$ of the total angular momentum $\mathbf{L}$ and electron spin $\mathbf{s}_e$ and splits each level into two sublevels, corresponding to the eigenvalues $j = L \pm 1/2$.

Splitting values, defined as $\Delta E_L = E(j = L + 1/2) - E(j = L - 1/2)$, have been calculated in the first order of perturbation theory over H_s by using variational nonrelativistic wave functions [14]. These values for a number of states of ${}^4He\bar{p}e$ systems in the range $32 \leq L \leq 37$ are presented in Table 3.

Table 3. Splitting values $\Delta E_L(10^{-4}eV)$ of the ${}^4He\bar{p}e$ system.

$N \backslash L$	33	34	35	36	37
1	-.311	-.313	-.311	-.305	-.298
2	-.296	-.294	-.289	-.282	-.272
3	-.278	-.273	-.266	-.256	-.245
4	-.256	-.255	-.246	-.234	-.223
5	-.277	-.252	-.245	-.228	-.226

Experimentally, only the difference in splitting of two levels can be observed. Since the dependence of calculated splitting values on L is rather slow, it is not possible to resolve such a small difference in splittings for the favoured transitions, i. e. transitions between states of the same N. For this reason, the experimental proposal for near future [20] is aimed at searching the splitting in the unfavoured transitions $(L, N) \rightarrow (L-1, N+2)$.

The part of interaction depending on heavy particle spins removes the remaining degeneracy and split each $j = L \pm 1/2$ sublevel further into two or four levels for ${}^4He\bar{p}e$ and ${}^3He\bar{p}e$ systems, respectively. Values of this secondary splitting are much smaller in comparison with the initial splitting.

6 Formation probability and initial populations

The calculation of the formation probability and initial populations of antiprotonic helium atoms is important for the understanding of cascade processes and the interpretation of experimental data. Antiprotonic helium atoms are produced in the reaction of the antiproton capture by a helium atom with an electron emission. As antiprotons mainly loose energy in inelastic collisions, one can assume that their initial kinetic energy does not exceed the ionization energy of helium atoms. Calculations of the antiproton capture and slowing down in helium [21], made in the framework of semiclassical model, confirm this assumption.

The formation probability of 0.22 for one stopped antiproton, calculated in this paper, is far from the experimental value $0.03 - 0.04$. The possible reason for this difference is due to the model used in the calculation. One can mention that calculated energies of the considerable part of final states are smaller in comparison with results of precise calculations.

The important qualitative result, obtained in this calculation, is a strict connection on the initial kinetic energy of an antiproton and the total angular momentum of the formed antiprotonic helium atom. As a consequence of this connection the formation of antiprotonic helium atoms with the fixed angular momentum is due to a capture of an antiproton with the fixed energy.

Another approach, used quasi-classical conceptions, have been applied to the calculation of initial populations of antiprotonic helium atoms [22]. Lower bound for the populations of antiprotonic helium atoms have been obtained. Thus, only states of the large enough L and N values can be formed. Full formation probability in this calculation is about 0.3 per one stopped antiproton and also differs from the experimental value.

Up to now, the experimental information on populations of states for $N = 3, 4$ near the metastability boundary have been obtained [9,18]. One can mention the necessity of the reliable calculations of the formation probability and initial populations by using few-body methods for the precise solution of this problem.

7 Interaction with helium medium

The interaction of antiprotonic helium atoms with the surrounding medium plays a crucial role in its survival. The angular momentum and energy transfer is hindered due to the neutrality of antiprotonic helium, screening of the antiproton by the electron and large excitation energy of the ordinary helium atom. This qualitative arguments are supported by the experiment [3,23], where only a small, although significant, density dependence of the delayed annihilation time spectra have been found.

At the same time an average antiproton lifetime, transition lifetimes and a fraction of the so-called fast component in the delayed annihilation time spectrum depend on density. An average antiproton lifetime depends also on the phase of the helium medium and its value in solid helium is 20 percent shorter than in liquid helium of the same density. One more problem is the observed isotope dependence of the decay rate of the fast component [23]. One should obtain the quantitative description of the existing density and phase dependence.

Only calculations of the ordinary helium atom – antiprotonic helium interaction were obtained [22] in the framework of multi-channel approach. The quenching of the delayed annihilation due to processes

$$\bar{p}He^{+}(L_i N_i) + He \rightarrow \bar{p}He^{+}(L_f N_f) + He$$

in collisions with surrounding helium atoms has been considered. Main conclusions are as follows:
The states with $L + N \leq 40$ are stable against collisional quenching at all densities up to the density of liquid helium. The states with $L + N = 41$ are intermediate: they are destroyed by collisions at high densities. The states with $L + N \geq 42$ are fully destroyed at $p \geq 1bar$, and can survive at very low densities ($p \sim 1mbar$).

One can conclude that the influence of medium on antiprotonic helium atoms, including the external Auger effect, collisional de-excitation, collisional broadening of radiation spectral lines and solid phase effect are still awaiting for their investigation.

8 Quenching by impurities

The effect of impurities on the delayed annihilation was discovered in experiment [2,3,24]. The admixtures of noble gases (Ne, Ar, Kr) of order 10 percent shorten the average $\bar{p}$ lifetime slightly. The effect of molecular gases (H_2, N_2, O_2) is noticeable at impurity concentrations as low as $20ppm$. For the most investigated case of the molecular hydrogen the following estimate for the quenching cross-section σ_q was found: $\sigma_q v = 6 \cdot 10^{-11} cm^3/s$. Thus the quenching cross-section is close to the geometrical cross-section, i. e. metastable states are destroyed in a single collision with a hydrogen molecule.

The qualitative understanding of these facts is based on the easy possibility to transfer the angular momentum to a diatomic molecule. On the contrary, such a possibility does not exist for noble gases due to large excitation energies.

Up to now there are no calculations of the interaction of antiprotonic helium atoms and another atoms or molecules. At the same time, delayed annihilation time spectra reveal some peculiarities in the dependence on the impurity concentration. As a result, the theoretical study is necessary to provide the quantitative description of observed quenching phenomena.

9 Other exotic systems and reactions

The discovery of antiprotonic helium atoms caused searching of other long-lived systems with an antiproton. The most probable candidates are systems consisted of an antiproton captured by the noble gas atom. Another possibility is the antiprotonic lithium and energies of this system were calculated in [10]. However, no delayed annihilation was detected experimentally in gaseous Ne [3], metallic Li and LiH [23]. Calculations of formation and quenching rates in these media are necessary to clear up the situation.

Besides of neutral antiprotonic helium atoms, $\bar{p}He$ systems of charge -1 can be formed [25] due to the attractive polarization $\bar{p} - He$ potential. If these systems survive for sufficiently long time, they can contribute to the kinetics of antiprotons in media.

New exotic systems can be produced in reactions of long-lived antiprotonic helium atoms with other atoms and molecules. In particular, the reaction

$$\bar{p}He^+ + Ps \rightarrow \bar{H} + He$$

was proposed [26] for the antihydrogen production. One can assume also the possibility of exotic molecules, which include as a part the antiprotonic helium atom.

10 Conclusion

Nowadays new three-body systems are discovered and intensively investigated both theoretically and experimentally. The description of these exotic systems meet some difficulties due to metastability and the extremely large total angular momentum $L \sim 30 - 40$.

There is the principal possibility to study antiproton properties by using measurements of antiprotonic helium atoms.

A number of problems arise in the theoretical treatment of intrinsic properties of antiprotonic helium atoms, their formation and collisions with atoms and molecules.

These problems represent a wide area for the application of few–body methods of calculations.

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