Delayed antiproton annihilation in light atoms

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A mechanism for delayed annihilation in $He^+\bar{p}$ and $Li^+\bar{p}$ clusters is analyzed in the coupled-channel model. A cascade of virtual Auger transitions is shown to be the primary mechanism for the decay of metastable antiproton states in atoms with $Z>2$. The lifetime of the long-lived fraction ($\sim 1\%$) of the antiprotons captured in atomic Li is predicted to be on the order of 10^{-7} s.

In a recent experiment [1] at the LEAR low-energy antiproton storage ring at CERN, confirmation was found for the earlier observation [2] of an unusually long lifetime for antiprotons stopped in helium ($\sim 10^{-6}$ s) in comparison with the time characteristic of atomic processes ($\sim 10^{-12}$ s). This long lifetime was characteristic of only a small fraction ($\sim 3\%$) of the antiprotons which are stopped, and it was observed only in He. In the case of many-electron atoms (Ar, Ne, N), this delayed annihilation disappeared completely. A corresponding observation has been made in the reaction of K^--meson capture, [3] but that process was difficult to study because of the short intrinsic lifetime of the K^- meson. A possible mechanism [4] which leads to a qualitative understanding of the reasons for this effect involves the formation of an atomic cluster $(\alpha e\bar{p})^*$ in the reaction

$$\mathrm{He}+\bar{p}\rightarrow(\alpha e\bar{p})^*+e. \tag{1}$$

The states of the antiproton in the $(\alpha e\bar{p})^*$ cluster are characterized by a large main quantum number ($N\sim 40$) and by a large angular momentum ($L\sim N-1$), while the remaining electron is in the $1s$ state. The lifetime of an antiproton in such a cluster (we are concerned here with only an isolated cluster; we will not discuss effects which stem from an interaction with the medium in the present letter) before annihilation with a nucleus is governed by two processes: Auger transitions, which arise from the interaction of the antiproton with the electron, and radiative transitions. It was shown in Refs. 5 that a direct Auger transition from the initial state of the antiproton ($N\sim 40$, $L\sim 39$) to the final state ($\tilde{N}\sim 33$, $\tilde{L}\sim 32$), corresponding to an opening of the channel with electron emission, turns out to be substantially suppressed in comparison with a cascade of radiative transitions. These transitions determine the duration of the delayed component ($\sim 10^{-6}$ s).

In this letter we are interested in the dynamics of Auger transitions in an isolated $(\alpha e\bar{p})^*$ cluster. We treat the three-body Coulomb system in the coupled-channel model, which has been used previously to study the $H\bar{p}$ system.[6] The approach we are taking here makes it possible to incorporate the decay of the antiproton through a cascade of virtual Auger transitions in a natural way. We show that the intensity of this decay mechanism is much higher than the intensity of the direct Auger transition in the regions

of N and L of interest here. We estimate the lifetime and the fraction of antiprotons corresponding to the delayed-annihilation effect in helium and lithium. The lifetime of narrow, metastable states in helium is governed by the intensity of radiative transitions, while the lifetime in an atomic cluster with two electrons, ($Li^+\bar{p}$), formed after the capture of the $\bar{p}$ by the Li atom is determined by a cascade of virtual Auger transitions and has a value no greater than 10^{-7} s for 1% of the stopped antiprotons. The reason is a sharp intensification of the mechanism of virtual cascade Auger transitions in multielectron clusters. In atoms with a large number of electrons, the lifetime is close to the normal atomic lifetime ($\sim 10^{-12}$ s).

To find the widths of the metastable states we use the formalism developed in Refs. 6 and 7. The basic idea of this approach is to introduce two components of a three-body wave function, each of which describes one of two asymptotic clusters: $(\alpha e)\bar{p}$, and $(\alpha\bar{p})e$. The $(\alpha e)\bar{p}$ cluster corresponds to states in which the electron is in a bound state in the field of the αparticle, and the antiproton is removed to a large distance. In the $(\alpha\bar{p})e$ cluster, on the other hand, the antiproton is in the field of the αparticle, and the electron is removed to a large distance. After an expansion of each of these two components of the three-body wave function in the bases of two-particle wave functions of the corresponding clusters, we find a system of coupled-channel equations. An advantage of a system of equations of this sort is that it gives a correct description of the asymptotic behavior of the three-body wave function. A comparatively small number of basis functions (channels) is therefore sufficient for evaluating the Auger widths and the positions of the metastable levels in a first approximation.

Let us take a more detailed look at the mechanism for decay of metastable antiproton states through a cascade of virtual Auger transitions. As we will see below, this mechanism is more probable than a direct Auger transition from highly excited antiproton states $N, L>40$ to low-lying states $N, L\sim 32$, corresponding to ionization of the $(\alpha\bar{p})e$ cluster.

To simplify the discussion we adopt as an example the case of three coupled channels, each corresponding to a state of an antiproton with definite values of N and L. We assume that the first and second channels are blocked. The first channel describes the bound state of the antiproton with quantum numbers (N,L) in the field of an α, partially screened by the $1s$ electron. The second channel corresponds to the virtual excitation of the $2p$ state of the electron as an antiproton undergoes a transition from the (N,L) state to the $(N-1, L-1)$ state. We assume that the third channel is open and that it describes a state of the $(\alpha e\bar{p})^*$ cluster in which the electron can escape from the system. The equations describing this simple coupled-channel model are

$$
\begin{aligned}
|g_1\rangle &= \hat{G}_1(E_1)\hat{W}_{12}|g_2\rangle,\\
|g_2\rangle &= \hat{G}_2(E_2)\hat{W}_{21}|g_1\rangle + \hat{G}_2(E_2)\hat{W}_{23}|g_3\rangle,\\
|g_3\rangle &= \hat{G}_3(E_3)\hat{W}_{32}|g_2\rangle.
\end{aligned}
\tag{2}
$$

Here g_i is the channel wave function, $\hat{G}_i(E_i)$ is the channel Green's function operator, E_i is the channel energy ($E_1<0$, $E_2<0$, $E_3>0$), and W_{ik} is a transition potential. For simplicity we set $W_{13}=W_{31}=0$. This system of equations can be reduced to a single equation for a wave function of the metastable state g_1 by introducing an effective

nonlocal complex potential. The negative-definite imaginary part of this potential imparts a width to the metastable state. Using a perturbation theory in the transition potential, we easily find an expression for the effective potential and the width:

$$\hat{V}_{\text{eff}} = \hat{W}_{12}\hat{G}_2\hat{W}_{23}\hat{G}_3\hat{W}_{32}\hat{G}_2\hat{W}_{21}, \tag{3}$$

$$\Gamma(N,L) = -2\langle g_1^0 | Im V_{\text{eff}} | g_1^0 \rangle. \tag{4}$$

Here g_1^0 is the unperturbed wave function of the antiproton (without allowance for the coupling of channels) in the field of the α, screened by the $1s$ electron.

A cascade of virtual Auger transitions was analyzed in a realistic multichannel model[7] in the example of a single metastable state ($N=44$, $L=43$). An expression analogous to (4) was derived (by a perturbation theory in the transition potential) for the width of the metastable state:

$$\Gamma = -2\langle \psi_{1s}\chi_{N,L} | WG_{N-1,L-1}f_{N-1,L-1}...WImG_{\tilde{N},\tilde{L}}W...f_{N-1,L-1}G_{N-1,L-1} | \chi_{N,L}\psi_{1s} \rangle. \tag{5}$$

Here ψ_{1s} is the wave function of the $1s$ state of the electron, $\chi_{N,L}$ is the unperturbed wave function of the antiproton in the state with main quantum number N and angular momentum L, $G_{n,l}$ is the Green's function of intermediate states of the electron, $G_{\tilde{N},\tilde{L}}$ is the electron Green's function of the open channel, and $W = 1/|\mathbf{R}-\mathbf{r}|$ is the electron–antiproton interaction potential ($\mathbf{R}$ is the coordinate of the antiproton, and $\mathbf{r}$ is the coordinate of the electron). In deriving (5) we assumed that only transitions between states of the antiproton, for which the condition $\Delta L < 2$ holds, are nonzero. This simplification is justified by the circumstance that the matrix elements of the transition potential between states with different L fall off rapidly with increasing ΔL (a unit change in ΔL leads to a decrease in the matrix element of the transition potential by an order of magnitude). As can be seen from (5), the expression for the width of the metastable state, which arises from decay of the antiproton through a cascade of virtual transitions, contains a product of $2\Delta L$ terms, where $\Delta L = L - \tilde{L}$ is governed by the difference between the angular momentum of the state of interest ($N=44$, $L=43$) and the angular momentum of the open channel ($\tilde{N}=33$, $\tilde{L}=32$).

The value of $\Gamma(N,L)$ found through a numerical calculation turns out to be $4\times 10^1\ \text{s}^{-1}$ for $N=44$, $L=43$. To compare this result with the characteristic atomic width $\Gamma_{\text{atom}} = 10^{12}\ \text{s}^{-1}$, it is convenient to rewrite the former in the form

$$\Gamma(N,L) = \beta^{2\Delta L}(N,L)\Gamma_{\text{atom}}. \tag{6}$$

Taking the structure of expression (5) into account, we have introduced an Auger-transition suppression factor $\beta^{2\Delta L}(N,L) = \Gamma(N,L)/\Gamma_{\text{atom}}$. For the $N=44$, $L=43$ state ($\Delta L = 11$), the value of this factor is 10^{-11}. The parameter $\beta(N,L)$ gives an idea of the average size of the suppression factor per transition; its value for the $N=44$, $L=43$ state is ~ 0.3. [We wish to stress that $\beta(N,L)$ is an average quantity over the cascade. The value found for $\beta(N,L)$ refers to a definite metastable state. Using it to calculate the Auger widths of other states would be wrong.] Expression (6) makes it possible to demonstrate explicitly the fact that the low intensity of Auger transitions stems from the large number of transitions within the cascade, while the average intensity of an individual virtual transition, characterized by the parameter β, is appreciable. We note that

the intensity of the cascade Auger transition estimated above is substantially higher than that of a direct Auger transition from the $N=44$, $L=43$ state to a state corresponding to the open channel, $N=33$, $L=32$ (the difference is two orders of magnitude). The reason for this small value for the direct Auger transition is that the initial state of the electron is the $1s$ state, while the final state is a state in the continuum with an angular momentum ΔL. The overlap of the wave functions of these states is exceedingly small, and it falls off rapidly with increasing ΔL.

The lifetime of the $\bar{p}$ in the $N=44$, $L=43$ state in the $(\alpha e\bar{p})^*$ cluster with respect to Auger transitions is 3×10^{-2} s. This time is substantially longer than the lifetime for radiative transitions, [8,9] which is on the order of 10^{-6} s. Accordingly, it is specifically radiative transitions that determine the lifetime of the delayed component of antiprotons in helium.

Evaluating the role played by the cascade of virtual Auger transitions turns out to be important for explaining the fact that the delayed-annihilation phenomenon is not observed when many-electron atoms are used as targets. To clarify, if we assume that in a multielectron cluster formed through the capture of an antiproton by an atom the latter interacts independently with each electron of the cluster, then within the framework of perturbation theory the intensity of each of the virtual transitions increases by a factor of n, where n is the number of electrons in the cluster ($n=Z-1$, where Z is the atomic number of the multielectron atom). Consequently, the width of the metastable state of the multielectron cluster can be calculated from

$$\Gamma_{\text{multi}}(N,L)=(n\beta(N,L))^{2\Delta L}\Gamma_{\text{atom}}. \tag{7}$$

The width of the metastable state of the multielectron cluster, which arises because of the cascade of virtual Auger transitions, is thus larger than in helium by a factor of $n^{2\Delta L}$ (for the same values of N and L). For antiprotons in lithium, the lifetime of the $N=44$, $L=43$ state estimated from (7) is no greater than 10^{-7} s. For atoms with $Z>3$, the lifetime of the captured antiprotons is on the order of the ordinary atomic times, and the delayed annihilation is not observed.

Let us now find the fraction of the antiprotons which are stopped in helium and which have a long lifetime (long in comparison with atomic times). Actually, we should estimate the probability P for the capture of an antiproton by a He atom into orbits with a large angular momentum ($L\sim40$), since—as can be seen from the analysis above—the lifetime is governed by the quantity $\Delta L=L-\tilde{L}$. To find a qualitative estimate, we treat the motion of an antiproton as the motion of a classical particle along a rectilinear trajectory. We also assume that the antiproton is captured by a He atom only if the energy of the antiproton does not exceed the threshold for target decay (25 eV), and the impact parameter does not exceed the first Bohr radius. We furthermore assume that the energy of the antiprotons which are captured is distributed uniformly from 0 to 25 eV, since the initial energy of the beam of antiprotons incident on the helium target is much greater than 25 eV (this initial energy is several tens of keV). Under these assumptions we find the following expression for the capture probability: [8]

$$P\sim1-2(L/L_{\max})^2(\ln(L_{\max}/L)+0.5). \tag{8}$$

Here $L_{max}=52$ is the maximum angular momentum which a captured antiproton can have. It corresponds to a maximum energy of 25 eV and to a maximum impact parameter

$$L_{max}=r_{1s}\sqrt{2ME_{ion}}. \tag{9}$$

Here r_{1s} is the radius of the $1s$ state of the electron in helium, and E_{ion} is the ionization potential. For the fraction of antiprotons in helium which have a lifetime on the order of 10^{-6} s, we find a value on the order of 4%. This figure is close to the value found experimentally. (The question of the fraction of long-lived antiprotons in helium was studied in more detail in Ref. 10.) To find an estimate analogous to (8) for the case of Li, we need to alter the value of L_{max}, substituting the radius of the $2s$ state and the ionization potential of the outer electron of Li into expression (9). For the 1% of the antiprotons which are stopped in Li, the lifetime is estimated to be on the order of 10^{-7} s.

The estimates derived in this paper are semiquantitative, while the formalism proposed here can be used to calculate the energies and widths of metastable states of an $(\alpha e\bar{p})^*$ cluster with a prespecified accuracy. The results of corresponding calculations will be published.

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