Delayed antiproton annihilation in helium and the initial populations of $\bar{p}$He atomic states

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Using the experimental data on the time distribution of the annihilation events, we demonstrated that the initial populations of nl levels of antiprotonic helium can be reconstructed.

Recently a new phenomenon was discovered in the process of negative hadron capture by helium. After forming a hadronic atom, pions, kaons or antiprotons are expected to be promptly absorbed because of the very fast deexcitation cascade. It was found, however, that in case of K^- capture a fraction of about 2% decays before reaching low-lying states.[1] The time distribution of the annihilation products after the $\bar{p}$ stop in helium, measured in the experiment,[2] revealed a delayed component with a trapping time of 3 μs and a fraction of 3%.

The conventional wisdom is that a hadronic helium is formed, by replacing one of the electrons with the negative hadron, in the state with the orbit size close to the electron Bohr radius, i.e., with the most probable principal quantum number n close to

$$n_0=(M/m_e)^{1/2}, \tag{1}$$

where M is the reduced mass of the atom, and m_e is electron mass. In the case of antiproton capture the system $[(\bar{p}\mathrm{He})_n e]$ is formed with $n \approx n_0 = 38$.

The possibility of trapping was pointed out in the old paper by Condo.[3] Because of the relatively large binding of the $1s$ electron in helium, the Auger deexcitation of the states with large n and l (close to circular orbits $l=n-1$) requires a large change in l ($\Delta l>3$), and therefore is strongly suppressed. Since the remaining electron prevents the Stark mixing, the near-circular states deexcite slowly via the sequence of the dipole radiative transitions with a small Δn. A more detailed treatment of the energy spectra and the deexcitation rates for exotic helium atoms was given by Russel,[4] who considered the possibility of trapping.

The lifetime of the circular state with $n=38$ determined by the radiative deexcitation rate is 0.7 μs, according to Ref. 4. Taking into account the atomic core polarization,[5,6] we obtain the lifetime of about 2 μs. This value is in order-of-magnitude agreement with the lifetime of the slowest component, $\tau_0=(3.04\pm0.07)$ μs, observed in Ref. 2. However, the measured time distribution of the annihilation events, which can be represented as a sum of several exponential distributions with various disappearance rates,[2] is still a problem. Given the initial state with $l=n-1$

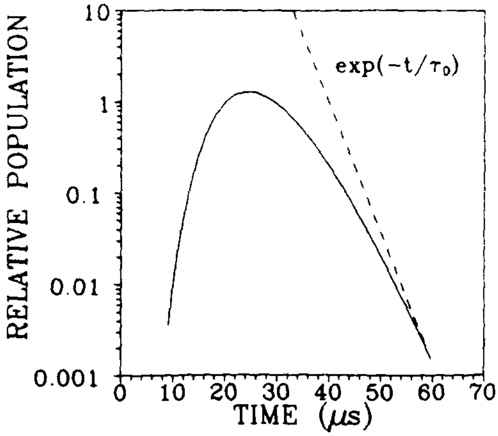

FIG. 1. The time dependence of the population of the state $(n,l)=(30,29)$ in the case where only one state $(n,l)=(51,50)$ is populated at the initial moment $t=0$.

and $n \gtrsim n_0$, the calculated absorption time distribution is markedly different from the one given by the exponential law and it exhibits a buildup region with a time scale comparable with the one given by the disappearance rate (see Fig. 1).

Our goal in this study was to determine whether the observed time distribution can be reproduced with a proper choice of the initial population of the states *nl*, with the trapping provided by the Condo mechanism.

In order to demonstrate the basic idea of the reconstruction of the initial population from the observed time distribution, we consider a simplified cascade model which describes the radiative transitions between the circular states.[1)] The populations $p_n(t)$ of the states $n(n=n_{\min},...,n_{\max})$ are determined by the system of equations:

$$\frac{dp_n}{dt}=-\lambda_n p_n+\lambda_{n\leftarrow(n+1)}p_{n+1}. \tag{2}$$

Here λ_n is the total disappearance rate for the state n, $\lambda_{n\leftarrow(n+1)}$ is the rate of the transition from the state $(n+1)$ to the state n, $\lambda_n=\lambda_{(n-l)\leftarrow n}$.

A standard procedure is to solve the system (2) for the given initial conditions. In contrast with this procedure, we assumed that the time dependence $p_{\min}(t)$ is given. The problem, therefore, is to find the initial populations $p_n(0)$. This problem can be easily solved by using the standard method of eigenstates and eigenvectors, but in our particular case, even a more simple method works. Using the ansatz

$$p_{n_{\min}}(t)=\exp(-t/\tau_0), \tag{3}$$

we find

$$p_n(t)=c_n\exp(-t/\tau_0), \tag{4}$$

where the coefficients $Cn_{\min}+1,...,Cn_{\min}+k,...$ are determined by recursion. The necessary condition for the solution to exist is $\tau_0=1/\lambda_i$ for a state *i*, so that $c_n=0$ at $n>i$.

A typical example of the initial population which provides a *single exponent* time distribution at the end of the cascade is shown in Fig. 2. The deexcitation rates[7] were

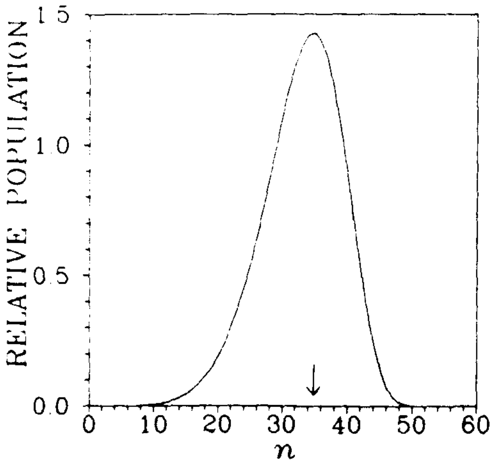

FIG. 2. The initial population of the circular orbits, which results in a single-exponent time dependence with the slope $\tau_0=3.0\ \mu s=\lambda_{51}^{-1}$.

calculated for hydrogen-like atom with an effective charge Z_{eff} which takes the electron screening into account according to Ref. 4, but polarization corrections[5,6] were not included for simplicity. For the trapping time corresponding to the measured one, $\tau_0=3.0\ \mu$s. we found the initial population distribution to be centered at $n=34$, i.e., very close to the mass scaling estimate n_0, while the highest state in the cascade chain is $n=i=51$ $(\tau_0\approx 1/\lambda_{51})$.

As a next step toward a realistic cascade model we take into consideration all the sublevels with $l\geqslant l_{min}$.[2)] Since there are no loops in the cascade without Stark mixing, the set of eigenstates coincides with the set of the total deexcitation rates:

$$\lambda_{nl}=\sum_{n'l'}\lambda_{n'l'\leftarrow nl}. \tag{5}$$

Since the number of eigenstates increases significantly, it becomes possible to find several of them with the eigenvalues close to the given value of $1/\tau_0$. For example, the states $(n,l)=(51,50)$, $(52,48)$, $(52,49)$, $(53,47)$, $(54,45)$,..., $(70,31)$ have the lifetime $1/\lambda_{nl}$ within the limits $(3.04\pm 0.09)\ \mu$s. Any proper normalized superposition of the corresponding eigenstates may also fit the observed delayed component. As a result, the solution to the problem of finding the initial population from the observed time distribution is not unique.

To approach the real situation, we have to take into account the Auger deexcitation. The Auger transitions favor the minimum possible change in the principal quantum number, thus feeding the near-circular orbits, and the Auger transitions with a small change in angular momentum are fast on the time scale considered[2] and do not contribute significantly to the trapping time. Taking these features into consideration, we find the region in the plane (n,l) with relatively large values of n and $l,n\geqslant 28$ and $l\geqslant 27$ (Ref. 7), where the radiative transitions dominate the cascade in the $[(\bar{p}\mathrm{He})e]$ system. As was demonstrated earlier, there exists a set of initial populations of the levels in this region which account for the delayed component described by the expo-

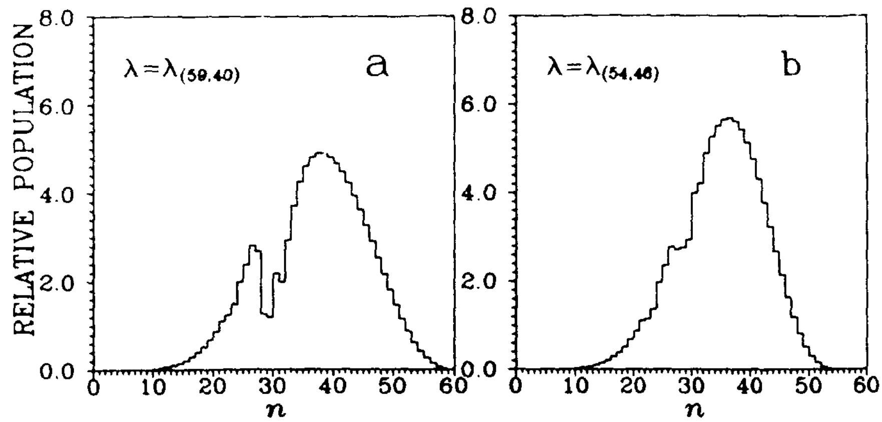

FIG. 3. The relative populations of n states at $t=0$ for two examples of eigenstate solutions with $\tau_0 \approx 3.0\ \mu s$: (a) $\lambda=\lambda_{(59,40)}$, (b) $\lambda=\lambda_{(54,46)}$.

nential law. The initial populations of levels with small n and l are irrelevant to the trapping, and the deexcitation of these levels contributes to the prompt annihilation peak.

Figures 3 and 4 show two typical examples of the population distributions for the eigenstates with eigenvalues λ_{nl} at $(n,l)=(54,46),(59,40)$ chosen in accordance with the observed disappearance rate of the delayed component. The distributions over n (Fig. 3) are very similar to those found in the simplified model (Fig. 2) with the maximum close to $n_0=38$. A structure in the left slope of this distribution is due to the fast Auger transitions that occur near $n=30$. The l distributions for the given n are well localized, as shown in Fig. 4.

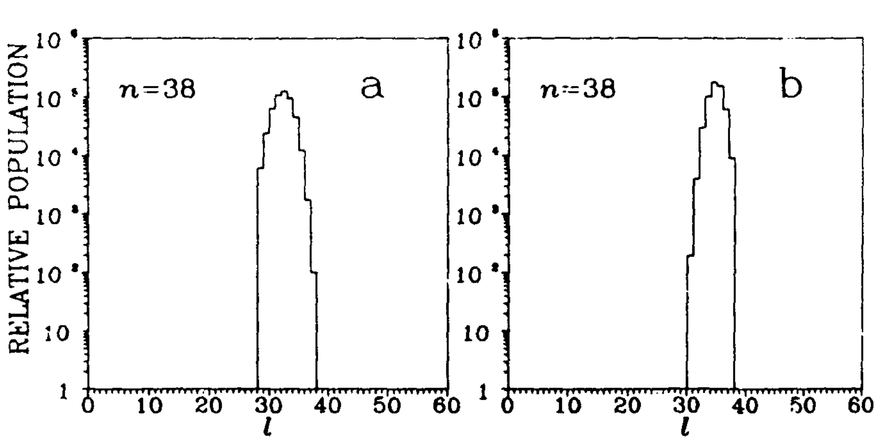

FIG. 4. The l-distribution at the state $n=38$ for the eigenstate solutions shown in Fig. 3.

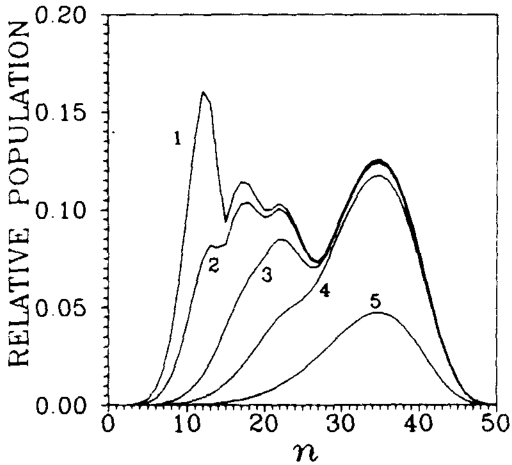

FIG. 5. An example of the time evolution of the populations which reproduce the experimental time distribution.[2] Curves 1–5 correspond to the times 0.4 ns, 5 ns, 40 ns, 0.4 μs, 2 μs.

In Ref. 2 the annihilation time distribution in the time interval 0.4 sec$\leqslant t \leqslant$20 μsec was fitted with the sum of four exponential functions. By choosing the proper eigenfunctions one can also fit these experimental data. Using our cascade model and taking only the circular orbits into account, we calculated the distributions over n at various instants of time (Fig. 5). A four-peak structure at a small time corresponds to the four exponent fit of the experimental data (the real distribution may differ from the plotted one when the fast Auger deexcitation for the states with medium l is taken into account).

Our results should be considered as an estimation of the basic characteristics of the real initial populations in antiprotonic helium, because the simplified model of the cascade was used. Further improvements, including the electron polarization effects in the radiative transitions[5,6] and taking into account the Auger transitions, should be made in order to obtain more accurate results for initial populations and to investigate the density dependence of the delayed annihilation. It would be also desirable to compare the initial populations, obtained in this manner, with the theoretical predictions for the capture process.

In conclusion, we have demonstrated that a set of initial populations of antiprotonic helium, which produce, as a result of a cascade, the delayed component in the time distribution of the annihilation events, can be found. This delayed component is described by a *single exponent law*, and therefore the buildup problem can be removed by using a proper distribution over nl states at the initial stage of the cascade. The trapping results from the multistep radiative deexcitation, as suggested by Condo.[3] Using the slowest delayed component ($\tau_0 = 3.0$ μsec) observed in the experiment,[2] we found that the initial distribution over the principal quantum numbers n is centered near $n_0 = 38$, in accordance with the mass scaling estimate (1). Since there exist many eigenstates with the values close to the observed disappearance rate, the reconstruction of the populations is not unique. Additional information or theoretical considerations are required to eliminate this ambiguity. The data on delayed radiative transitions between highly excited states would be very useful for this purpose.

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[1)]One may keep in mind that for the radiative transitions in a hydrogen-like atom the rate λ_n is a monotonically decreasing function of n, and $\lambda_n \sim n^{-5}$ at large n.
[2)]The states with $l < l_{min}$ are assumed to undergo a fast deexcitation via Auger transitions, see below.

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[1]T. Yamazaki, M. Aoki, M. Iwasaki *et al.*, Phys. Rev. Lett. **63**, 1590 (1989).
[2]M. Iwasaki, S. N. Nakamura, K. Shigaki *et al.*, Phys. Rev. Lett. **67**, 1246 (1991).
[3]G. T. Condo, Phys. Lett. **9**, 65 (1964).
[4]J. E. Russell, Phys. Rev. Lett. **23**, 63 (1969); Phys. Rev. **188**, 187 (1969); Phys. Rev. **A1**, 721, 735, 742 (1970).
[5]T. Yamazaki and K. Ohtsuki, Phys. Rev. A **45**, 7782 (1992).
[6]I. Shimamura, Phys. Rev. A **46**, 3776 (1992).
[7]B. L. Drujinin, A. E. Kudryavtsev, and V. E. Markushin, Preprint ITEP-2-93, Moscow, 1993.

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