THE DELAYED ANTIPROTON ANNIHILATION IN HELIUM AND THE INITIAL POPULATIONS OF $\bar{p}$He ATOMIC STATES

*B.L.Druzhinin, A.E.Kudryavtsev, V.E.Markushin**

Institute for Theoretical and Experimental Physics
127562 Moscow, Russia

**Russian Research Center, Kurchatov Institute*
123282 Moscow, Russia

Submitted 25 Juni 1993

Using the experimental data on the time distribution of the annihilation events we demonstrate the possibility to reconstruct the initial populations of nl levels of antiprotonic helium.

Recently a new phenomenon was discovered in the process of negative hadrons capture by helium. After forming hadronic atom, pions, kaons or antiprotons were expected to be promptly absorbed because of the very fast deexcitation cascade. However, it was found 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 $\bar{p}$ stop in helium, measured in experiment [2], revealed a delayed component with a trapping time of 3 μs and a fraction of 3%.

A 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 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 $[(\bar{p}\mathrm{He})_{nl}e]$ is formed with $n \approx n_0 = 38$.

A possibility of trapping was pointed out in the old paper by Condo [3]. Due to the relatively large binding of $1s$-electron in helium the Auger deexitation of the states with large n and l (close to circular orbits $l = n - 1$) requires large change of 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 small Δn. A more detailed treatment of the energy spectra and the deexcitation rates for exotic helium atoms was given by Russel [4], with the possibility of trapping being confirmed.

The lifetime of the circular state with $n = 38$ determined by the radiative deexcitation rate is $0.7\mu s$ according to [4]. With the atomic core polarization taken into account [5,6], one gets the lifetime about $2\mu s$. This value is close by the order of magnitude to the lifetime of the slowest component, $\tau_0 = (3.04\pm0.07)\mu s$, observed in [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 $l = n - 1$ and $n \approx n_0$, the calculated absorption time distribution is quite different from one given by the exponential law and exhibits a build-up region with a characteristic time scale comparable with one given by the disappearance rate (see Fig.1).

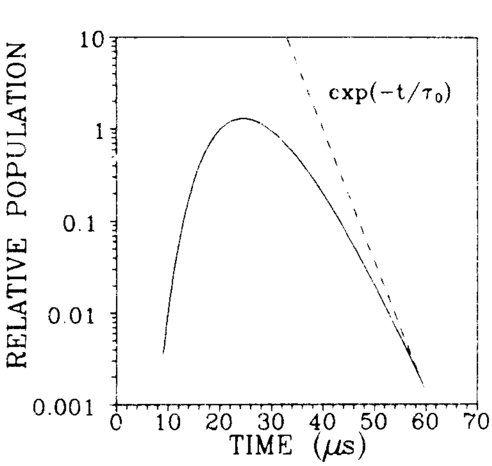

Fig.1.

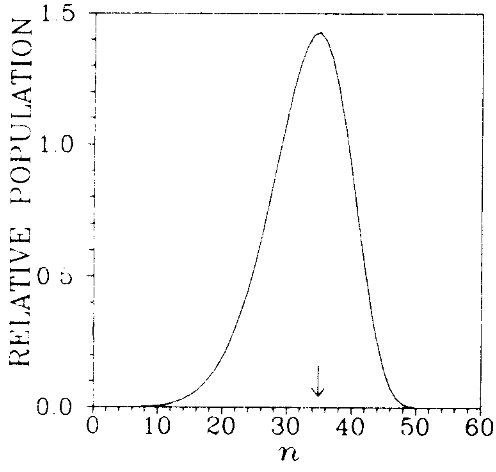

Fig.2.

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

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

The aim of this paper is to investigate 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 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 describing the radiative transitions between the circular states [1]. The populations $p_n(t)$ of the states n $(n = n_{min}, \ldots, n_{max})$ 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, $\lambda_n = \lambda_{(n-1)\leftarrow n}$.

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

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

we find

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

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

[1] One may keep in mind that for the radiative transitions in a hydrogen-like atom the rate λ_n is monotonously decreasing function of n, and $\lambda_n \sim n^{-5}$ at large n.

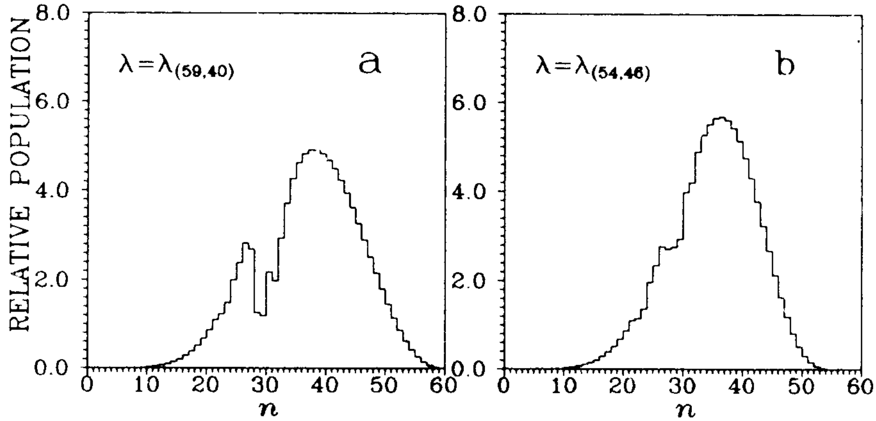

Fig.3. The relative populations of n states at $t=0$ for two examples of eigenstate solutions with $\tau_0 \approx 3.0\mu s$: (a) $\lambda = \lambda_{(59,40)}$, (b) $\lambda = \lambda_{(54,46)}$

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 calculated for hydrogen-like atom with effective charge Z_{eff} that takes the electron screening into account according to [4], but no polarization corrections [5,6] were included for the sake of 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 estimation n_0, while the highest state in the cascade chain in $n = i = 51$ ($\tau_0 \approx 1/\lambda_{51}$).

As a next step toward a realistic cascade model we take into consideration all the sublevels with $l \geq l_{min}$ [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 given value of $1/\tau_0$. For example, the states $(n,l) = (51,50), (52,48), (52,49), (53,47), (54,45), \ldots, (70,31)$ 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 Auger deexitation in consideration. The Auger transitions favor the minimum possible change in principal quantum number thus feeding the near-circular orbits, and the Auger transition with small change in angular momentum are fast on time scale considered [2] and do not contribute significantly to the trapping time. Taking these features into consideration one can find the region in the plane (n,l) with relatively large values of n and l, $n \geq 28$ and $l \geq 27$ [7], where the radiative transitions dominate

[2)] The states with $l < l_{min}$ are assumed to undergo fast deexcitation via Auger transitions, see below.

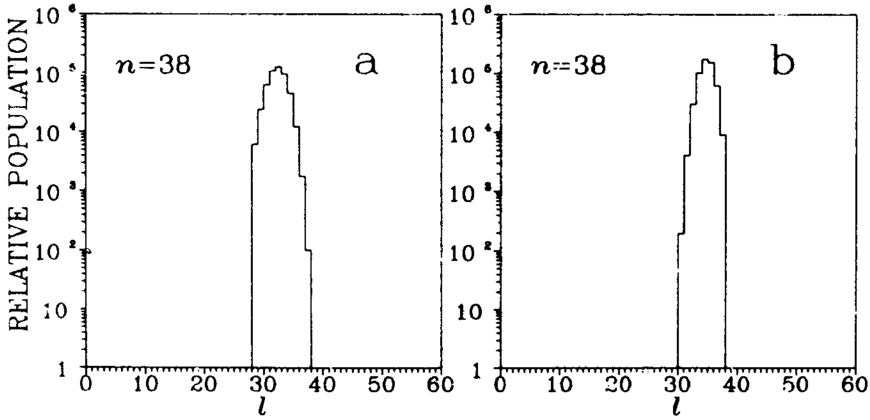

Fig.4. The l-distribution at the state $n = 38$ for the eigenstate solutions shown in Fig.3

the cascade in $[(\bar{p}\text{He})e]$-system. As it was demonstrated earlier, there exists a set of initial populations of the levels in this region which result in the delayed component described by exponential law. The initial populations of levels with small n and l are irrelevant to the trapping, the deexcitation of these levels contributing to the prompt annihilation peak.

Fig.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 that 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 possible near $n = 30$. The l distributions for given n are well localized, as it is shown in Fig. 4.

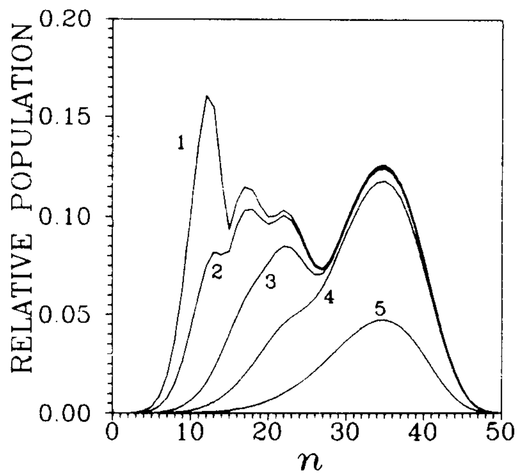

Fig.5. An example of the time evolution of the populations reproducing the experimental time distribution [2]. Curves 1-5 correspond to time 0.4 ns, 5 ns, 40 ns, 0.4 μs, 2 μs

In paper [2] the annihilation time distribution in the time interval $0.4sec \leq t \leq 20\mu sec$ was fitted with the sum of four exponential functions. By choosing proper eigenfunctions one can fit this experimental data as well. 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 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 bringing the Auger transitions into consideration, are to be done in order to get more accurate results for initial populations and to investigate the density dependence of the delayed annihilation. It would be also desirable to compare thus obtained initial populations with the theoretical predictions for capture process.

In conclusion, we have demonstrated that a set of initial populations of antiprotonic helium can be found which produce as a result of cascade the delayed component in the time distribution of the annihilation events. This delayed component is described by *single exponent law*, and therefore the build-up problem can be removed with using a proper distribution over nl states at initial stage of the cascade. The trapping results from the multi-step radiative deexcitation, as it was suggested by Condo [3]. Using the slowest delayed component ($\tau_0 = 3.0\mu sec$) observed in experiment [2] we found the initial distribution over the principal quantum numbers n being centered close to $n_0 = 38$ 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.

The authors thank Prof. T. Yamazaki and to Prof. V.S. Popov for discussions of preliminary version of this article.

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. **A45**, 7782 (1992)
6. I.Shimamura, Phys. Rev. **A46**, 3776 (1992).
7. B.L Drujinin, A.E.Kudryavtsev, and V.E.Markushin, Preprint ITEP-2-93, Moscow, 1993.