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THE DELAY ANNIHILATION IN HELIUM – 4. WHAT CAN WE LEARN FROM THIS EXPERIMENT ABOUT INITIAL POPULATIONS $\bar{N}(n,l)$ IN HADRONIC ATOM

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THE DELAY ANNIHILATION IN HELIUM-4. WHAT CAN WE LEARN FROM THIS EXPERIMENT ABOUT INITIAL POPULATIONS $\bar{N}(n,l)$ IN HADRONIC ATOM: Preprint ITEP 93-2/

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Using the experimental information on time dependence for the delay annihilation events, we reconstruct initial populations of (n,l)-levels of antiprotonic helium.

Fig. - 7, ref. - 7

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Recently a new and an extremely interesting phenomenon was found in the process of capture of slow negative kaons and antiprotons in helium target [1,2]. In case of K^--capture a sufficiently large fraction of stopped $K^-(\sim 2\%)$ was found decaying but not being absorbed by α-particles. In antiproton case the delayed annihilation in approximately 3.6 % of all the annihilation events was found.

First good and constructive idea to explain this phenomenon was given in the old paper by Condo [3]. His remark is that via the relatively large binding of $1s$-electron in helium (24.6 eV) the Auger-transition mechanism for deexitation of antiproton is strongly suppressed. So for certain atomic states (n,l) the most probable way for deexitation remains the emission of the dipole photon. For the orbits situated not far from circular orbits $(n, n-1)$ radiative transitions probabilities for large n are small enough. It provides relatively long timelife for such atomic states. The more qualitative estimates of some properties of hadronic helium were given in a series of papers by Russels [4].

Let us consider the case of $(\bar{p}e\alpha)$-atom. It is formed when one of the electrons of a helium atom is replaced by antiproton. The $\bar{p}$ occupies one of the atomic orbit with large n located in the same space as the $1s$-electron. Under this condition the most probable orbit has a principal quantum number n close to

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

where M^* is the reduced mass of the $\bar{p}\alpha$ see, for example, ref. [5]. So we get $n_0 = 38$.

According to Russels [4] the timelife on circular orbit with $n = 38$ is $0.7\mu sec$. Taking into account the atomic core polarization effects [5], one may get for this quantity the value $\approx 2\mu sec$. According to the paper [2] the most longly living component decays exponentially in ime.

$$N = N_0\, exp(-t/\tau_0) \quad , \tag{2}$$

with $\tau_0 = (3.04 \pm 0.07)\mu sec$. This quantity coincides by order with the timelife of antiproton on circular orbits for large $n \geq n_0$. So we got explanation for the delay component. But the time dependence for the

annihilation events is still problem. Really let us suppose that only the circular level with $n_0 = 38$ was initially populated. It is evidently that in this case we shall get for time dependence of annihilation the function which looks absolutely not like exponential function, observed in the experiment. This time dependence calculated using the routine cascade procedure, is shown in the Figure 1.

Let us discuss the problem - whether it is possible to find such initial populations of (n,l)-levels, which provides the observed exponential law for annihilaltion. Consider for the beginning a simplified chain version of cascade equations with transitions between circular orbits only included

$$\frac{dNi}{dt} = -W_{i,i-1}N_i + W_{i+1,i}N_{i+1} \qquad (i = 2,2,\ldots) \tag{3}$$

Here $W_{k,k-1}$ are the probabilities of radiative dipole transitions $k \to k-1$. Notice, that for large k

$$W_{k,k-1} \sim const/k^5 \tag{4}$$

So $W_{k,k-1}$ is monotonous decreasing function of k. It is suitable to look for solutions of eq.(3) beginning from the $1s$-level and then moving up to higher n. As we want to find solution for anninilaltion from $1s$-level with the given experimentally exponential law, we are making substitution

$$N_1(t) = \bar{N}_1 exp(-t/\tau_0) \tag{5}$$

and then get automatically $N_2(t) = \bar{N}_2 exp(-t/\tau_0)$, $N_3(t) = \bar{N}_3 exp(-t/\tau_0)$ etc. So all the populations $N_i(t)$ depend on time exponentially with the same τ_0. If τ_0 coincides with any $W^{-1}_{i,i-1}$ from the eq. (3), the so obtained set of $\bar{N}_i$ is finite with all $\bar{N}_i$ positive. We may call this solution the eigenfunction for the system (3). The typical picture of such a distribution $\{\bar{N}_i\}$ is given in the Figure 2.

Consider now the cascade equations with all types of possible states and transitions being included,

$$\frac{dN(n,l)}{dt} = \sum_{n',l'} W(n',l' \to n,l)N(n',l') - \sum_{n'',l''} W(n,l \to n'',l'')N(n,l) \tag{6}$$

Here $W(n,l \to n',l')$ are partial probabilities of transition $n,l \to n',l'$. It is suitable to introduce the quantity $W_0(n,l)$, which is total probability of decay for level (n,l),

$$W_0(n,l) = \sum_{n'',l''} W(n,l \to N'',l'') \tag{7}$$

It will be often used below. In the concrete calculation we shall use for $W(n,l \to n',l')$ the radiative dipole transition probabilities for hydrogen-like atom, using Gordon formulae [6], see also the monography [7]. The effective charge of screened α-particle was taken into account as factor which fits the probability $(38,37 \to 37,36)$ to that given in the Russels paper [4]. Figure 3 demonstrates the probabilities $W_0(n,l)$ of radiative transitions, calculated through the above mentioned procedure. One can see from this Figure, that there are links of states (n,l) with approximately the same eigenvalues $W_0(n,l)$. For example the states $(51,50),(52,48),(52,49),(53,47),(54,45),\ldots,(70,31)$ etc. have total decay rates $W_0(n,l)$ inside the limits $W_0^{-1}(n,l) \in (3040 \pm 90)nsec$. Notice that one may find eigenfunctions corresponding to each of these $N(n,l)$ eigenvalues with time dependence for each $N(n,l)$ in form

$$N(n',l) = \bar{N}(n',l')exp(-W_0(n,l)t) \tag{8}$$

We conclude that opposite to the simplified chain version (3) exact cascade equations (6) have set of solutions fitting experimental data. Any proper normalized superposition of these eigenfunctions may also fit to the experimental data. So the solution of the problem is not inambiguous.

To be more close to real situation we are to include Auger deexitation mechanism in addition to the radiative transition mechanism. Via Auger mechanism antiprotons make fast transitions to circular orbits. In our calculations we have limited ourselves by only incusion of

dipole Auger-transitions. The so obtained region in the plane (n,l), where radiative transitions play leading role, is shown in the Figure 4. So we conclude, that studing delay annihilation in helium, we may get information on initial populations of levels in $(\bar{p}e\alpha)$-system for relatively large n and l. Populations of levels with small n and l cannot be extracted from experiments of types [1,2]. The initial populations of these levels give contribution to the prompt annihilation events.

In the Figures 5 and 6 we demonstrate some curves of $\bar{N}(n,l)$ corresponding to different eigenfunctions of the eq.(6) with eigenvalues $W_0(54,56)$ and $W_0(59,40)$. Figure 5 gives examples of distributions $Z = log_{10}(N(n,l)/N(1,0))$ for some fixed n versus l. Histograms a, b, c correspond to $W_0(59,40)$ and d, e, f to $W_0(54,46)$. In the Figure 6 we give the corresponding distributions averaged over $n(\bar{N}(l))$, and over $l(\bar{N}(n))$. Histograms a,b refer to $W_0(59,46)$ and c,d to $W_0(54,46)$. Distributions $N(n)$ look like that what was got in the chain model (3) with maximum not far from $n_0 = 38$, see Fig. 2 for comparison. Some structure in these distributions on the left shoulders of the curves are connected with the fast Auger transitions near $n = 30$. Notice, that distributions $\bar{N}(l)$ have rather sharp maxima at some l_{max}. So these distributions do not look like statistical distribution $P(l) \sim 2l+1$. The maxima of these distributions look also more pronounced than in the distribution $P(l) \sim l \cdot ln(l/l_{max})$, discussed in the ref/ [5].

So we managed to reconstruct from the results of the experiment [2] the populations in antiprotonic helium at initial stage of cascade process.

Up to now we were discussing the most slowly decaying component of the delay annihilation with $\tau_0 = 3.04\mu sec$. In the experiment [2] the annihilation spectrum for time interval $0.4sec \leq t \leq 20\mu sec$ was fitted with the four different exponential functions. Notice that any superposition of eigenfunctions for the equation (6) is also the solution of the problem. So we may fit to the experimental data choosing proper eigenfunctions. This was done, and the corresponding populations of levels versus n summed over l are shown in the Figure 7 for several different time intervals. The time evolution of the solution is getting quite evident from this picture.

As it was mentioned above, there is a series of different eigenfunctions for the equation (6) with eigenvalues $W_0(n,l)$ which all are situated very close to the experimental number $W_{exp} = \tau_0^{-1}$. So the reconstrucred solution is not inambiguous. Studying time dependence of annihilation as it was done in the experiment [2] gives us no possibility to make distinction between different possible solutions. On the other hand we may get more detailed information on real populations of levels measuring energies and intensities of delay photons or/and delay Auger electrons. This will give us additional more refined information on initial populations of levels in antiprotonic helium.

In this article we presented only simple estimates of real populations in antiprotonic helium. The main reason is that we used a simplified hydrogen-like version for probabilities of radiative transitions. This and some other improvements is to be done to get more precise information on initial populations. It would be desirable to compare the so obtained distributions of initial populations with that follows from theoretical model for capture process.

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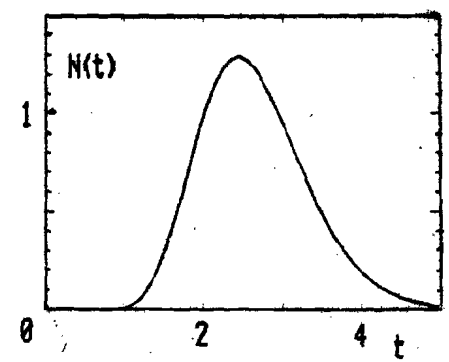

Fig.1. Population $\bar{N}(t)$ of the (30,29)-level versus time arbitrary units). The level (51,50) is the only one initially populated. Time scale is 10^{-5} seconds.

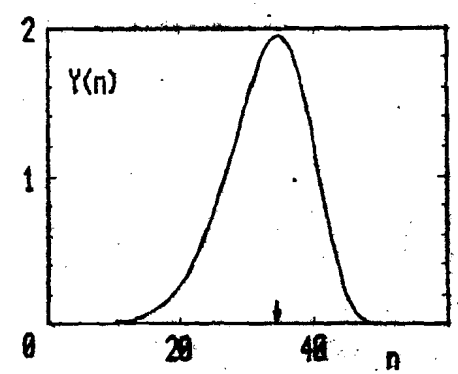

Fig.2. Distribution $Y = \bar{N}(n)/\bar{N}(1)$ for circular orbits versus n (in units 10^7). It corresponds to exponential decay law with slope $\tau_0 = 3040 nsec = W^{-1}(51)$. Arrow indicates position of maximum.

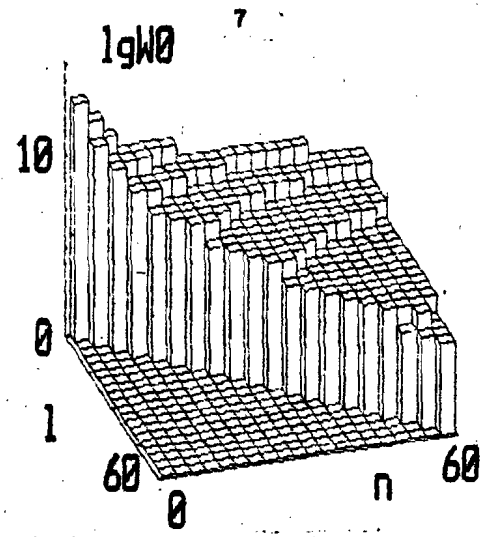

Fig.3. The dependence of probabilities of radiative transitions $W_0(n,l)$ on (n,l) plane. Integer parts of $log_{10}W_0$ are pictured. Results are summerized over squares 3x3 in (n,l)-plane

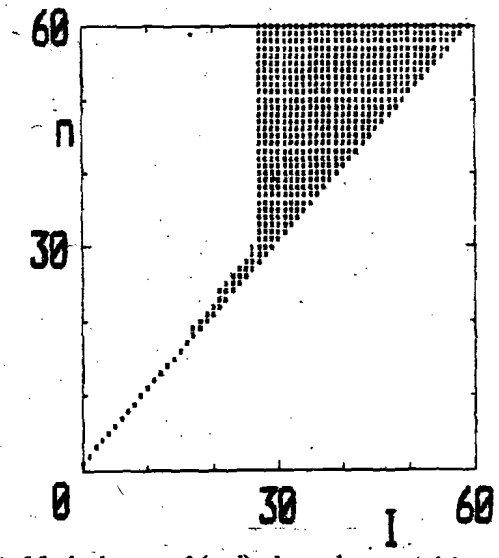

Fig.4. Marked part of (n,l)-plane shows positions of (n,l)-levels with leading role of radiative transitions.

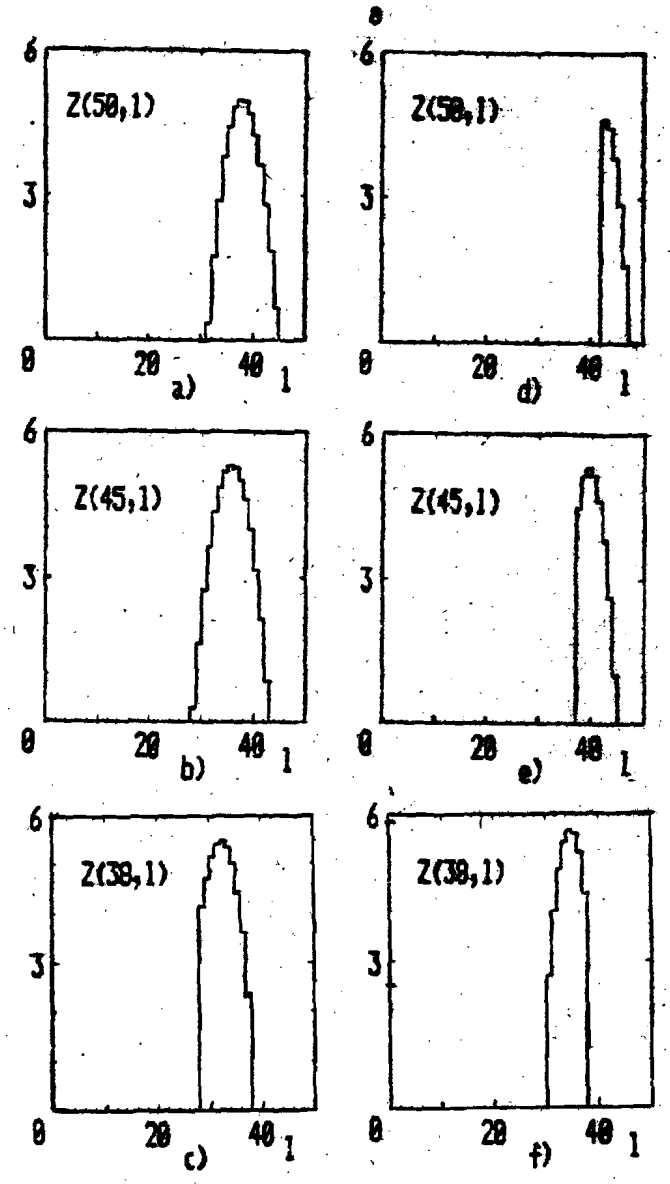

Fig.5. Typical distributions $Z(n,l) = log_{10}(\bar{N}(n,l)/\bar{N}(1,0))$

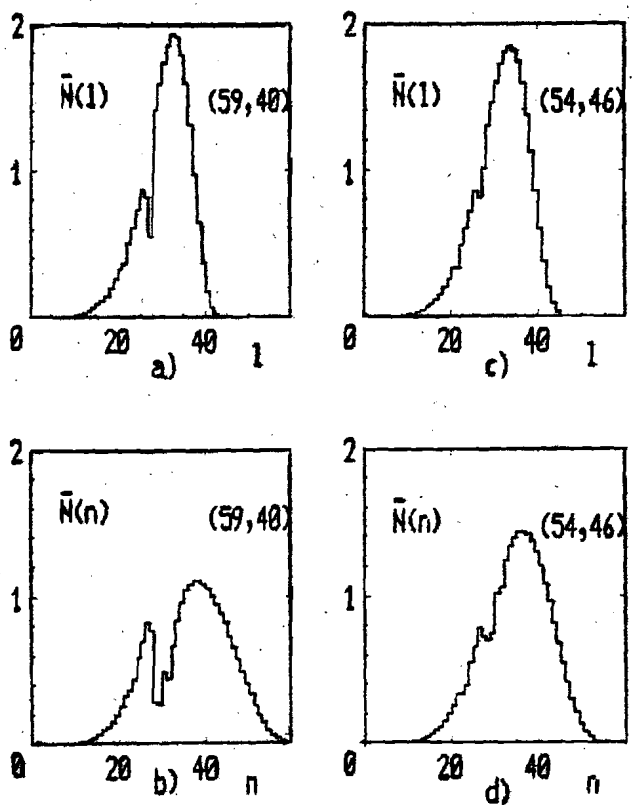

Fig.6. Distributions $Y(n,l) = \bar{N}(n,l)/\bar{N}(1,0)$ averaged over l and over n in units 10^5

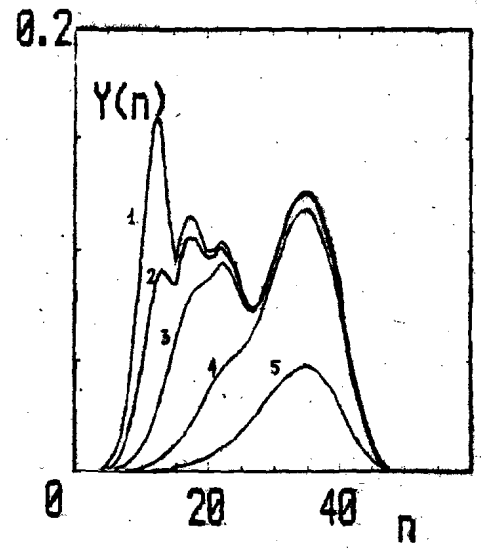

Fig.7. Examples of time dependent distributions $N(n)$, which reproduce experimental spectrum of the experimental spectrum of the ref. [2] for time initial $0.4nsec \leq t \leq 20000nsec$. Fit by four exponents used in [2] is reconstructed by four eigenfunctions containing circular orbits only. Curves 1-5 correspond to time 0.4 nsec, 5 nsec, 40 nsec, 400 nsec, 2000 nsec.

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Запаздывающая аннигиляция в гелии-4. Что можно узнать из этого эксперимента о начальных заселенностях $N(n, l)$ в адронном атоме.

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