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D.E.Kharzeev*, M.G.Sapozhnikov

NEUTRAL STRANGE PARTICLE PRODUCTION IN ANTIPROTON-NUCLEUS ANNIHILATION AT LOW ENERGIES

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*Institute for Nuclear Physics,
Moscow State University, Moscow, USSR

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Recent experiments [1-3] investigating strange particle production in antiproton-nucleus annihilation yielded results, that at first sight seemed unexpected. In the PS 179 experiment at LEAR [1,2] the production of Λ-hyperons and K_S^0 -mesons in antiproton annihilation on neon and ^{4}He was studied at 600 MeV/c. At this energy Λ production on a single nucleon is impossible, since the reaction threshold for $\bar{p}p \Rightarrow \Lambda\bar{\Lambda}$ is p_{th} = 1435 MeV/c, and associated production $\bar{p}N \Rightarrow \Lambda K$ is also forbidden. Nevertheless, the probability of Λ-hyperon production turned out to be significant, the ratio $R=\sigma(\Lambda)/\sigma(K_S^0)$ being $R = 2.3 \pm 0.7$ [1] and 0.94 ± 0.19 [2] for annihilation on neon and helium, respectively. A similar excess of Λ over K_S^0 was also observed in the annihilation of antiprotons in tantalum at 4 GeV/c [3], where it was found that $R=2.4 \pm 0.3$. An attempt made in ref. [4] at explaining the above fact by pion and kaon rescattering effects turned out to be unsuccessful. For explaining the abundant strange particle production in annihilation on tantalum Rafelski [5] put forward the hypothesis of the formation in this process of super-cooled quark-gluon plasma. However, before invoking various exotic explanations one must verify whether the traditional approaches are fully exhausted.

We have calculated the cross sections of the Λ and K_S^0 production in antiproton annihilation on nuclei at low energies ($E_{\bar{p}} < 200$ MeV) under the assumption that the sole source of the Λ be rescattering of the annihilation mesons. Besides π- and K-meson rescattering, we also have considered the production of Λ in reactions with ω- and η-mesons, since their lifetime is sufficiently long for their interacting with nucleons of the residual nuclei before decaying. It must be noted that the probabilities of ω- and η- meson production in antiproton annihilation are quite significant and amount 10% and 3%, respectively, of the total annihilation probability at low energies .

We considered the following two-step Λ-production processes:

$$\bar{p} + p \Rightarrow \pi^+ + \pi^- , \qquad \pi^+(\pi^-) + n(p) \Rightarrow \Lambda + K^+(K^0) \qquad (1a)$$

$$\bar{p} + p \Rightarrow \pi^0 + \pi^0 , \qquad \pi^0 + n(p) \Rightarrow \Lambda + K^0(K^+) \qquad (1b)$$

$$\bar{p} + n \Rightarrow \pi^- + \pi^0 , \qquad \pi^0(\pi^-) + n(p) \Rightarrow \Lambda + K^+, \text{ or } K^0 \qquad (1c)$$

$$\bar{p} + p(n) \Rightarrow K^-(\bar{K}^0) + X, \quad K^-(\bar{K}^0) + p \Rightarrow \Lambda + \pi^0(\pi^+) \qquad (2)$$

$$K^-(\bar{K}^0) + p \Rightarrow \Sigma^0 + \pi^0(\pi^+)$$

$$K^-(\bar{K}^0) + n \Rightarrow \Lambda + \pi^-(\pi^0)$$

$$\bar{p} + p(n) \Rightarrow \eta(\omega) + X , \quad \eta(\omega) + p \Rightarrow \Lambda + K^+ \qquad (3)$$

$$\eta(\omega) + p \Rightarrow \Sigma^0 + K^+$$

$$\eta(\omega) + n \Rightarrow \Lambda + K^0$$

$$\eta(\omega) + n \Rightarrow \Sigma^0 + K^0$$

Within the considered range of antiproton energies ($E_{\bar{p}} \le 200$ MeV) only those π-mesons that are produced in two-meson annihilation channels such as (1) may have an energy higher, than the Λ production threshold. The necessity of invoking the reactions with Σ^0 production channels is due to the nearly 100% probability of the subsequent rapid ($c\tau = 1.7 \cdot 10^{-9}$ cm) $\Sigma^0 \Rightarrow \Lambda\gamma$ decay.

The Λ-hyperon cross section was calculated from the following expression:

$$\sigma_{\bar{p}A \Rightarrow \Lambda X}(E_{\bar{p}}) = \sigma^{ann}_{\bar{p}A}(E_{\bar{p}}) \sum_M R^N_M(E_{\bar{p}}) \int_{E_{th,M}}^{\infty} F(E_{\bar{p}}, E_M) * P_M(E_M) * W_{MN \to \Lambda X}(E_M)\, dE_M, \qquad (4)$$

where $\sigma^{ann}_{\bar{p}A}(E_{\bar{p}})$ is the antiproton-nucleus annihilation cross section, $R^N_M(E_{\bar{p}})$ is the relative probability of the meson M production in $\bar{p}$N-annihilation, N stands for neutron or proton, $E_{th,M}$ is the threshold energy for the reaction $MN \Rightarrow \Lambda X$, $F(E_{\bar{p}}, E_M)$ is a function, normalized to unity, which describes the energy distribution of the annihilation mesons, $P_M(E_M)$ is the probability for a single interaction of the meson M to occur with the bound nucleon and $W_{MN \to \Lambda X}(E_M)$ is the probability of Λ production.

Eq. (4) was obtained under the assumption that the relative probabilities of different meson channels are the same in antiproton annihilation on bound and free nucleons. We also assumed the Λ-hyperons to be produced only in a single rescattering of the meson M on a nucleon of the nucleus,

$$W_{MN \to \Lambda X}(E_M) = P_M(E_M) \frac{\sigma_{MN \Rightarrow \Lambda X}(E_M)}{\sigma^{tot}_{MN}(E_M)}. \qquad (5)$$

We have used for $F(E_{\bar{p}}, E_M)$ in the c.m.s. the parametrization from [6]:

$$F(E^*_M) \sim \frac{k^2}{E^{*2}_M} \exp(- E^*_M / T_M). \qquad (6)$$

Here E^*_M and k are the center-of-mass total energy and momentum of the meson M, T_M is the "effective temperature" parameter of the meson energy spectrum. For kaons the value T_K = 84 MeV was taken [7]. It was assumed that $T_\eta = T_\omega = T_\pi$, where T_π = 117 MeV [8]. At the considered low antiproton energies the distribution (6) in the c.m.s. differs weakly from the corresponding distribution in the lab. system. For this reason we have substituted E_M for E^*_M in (6).

The relative probabilities of meson production $R^N_M(E_{\bar{p}})$ were taken from [9], where the most complete set of data for annihilation of stopped antiprotons on protons and neutrons are compiled. The $R^N_M(E_{\bar{p}})$ were assumed to be weakly dependent on the $E_{\bar{p}}$.

To determine the probability $P_M(E_M)$ of a single interaction of the meson M with a bound nucleon the following relation was applied in the considering annihilation on deuterium and helium:

$$P_M(E_M) = \frac{\sigma^{tot}_{MN}(E_M)}{4\pi} \left< \frac{1}{r^2_{NN}} \right>, \qquad (7)$$

where r_{NN} is the distance between the nucleons in the nucleus. For the deuteron wave function of the Hamada-Johnston type the quantity $4\pi / \langle r^{-2}_{NN} \rangle$ is 460 mb [10]. In the case of $\bar{p}^4$He annihilation it was estimated that for the factorized oscillator ^{4}He wave function $4\pi / \langle r^{-2}_{NN} \rangle$ is 120 mb .

In the case of $\bar{p}$Ne annihilation we put $P_M(E_M)$=1, i.e. each meson was considered sure to undergo interaction but only with one nucleon of the nucleus. The reason is that in neon, the characteristic condition for a single scattering to occur, $\lambda < R_{nucl.}$, where λ is the meson mean free path $\lambda = (\rho\, \sigma^{tot}_{MN})^{-1}$, starts to be obeyed. Actually, it is clear that a certain fraction of the mesons does not interact with the nucleus at all, whereas the remaining ones undergo multiple rescattering. Therefore, the adopted assumption may turn out to be a reasonable compromise between these two opposite tendencies.

The cross section for Λ production by π-mesons was taken from [11]. The cross section for reactions (2) $\bar{K}^0$ N $\Rightarrow \Lambda\, \pi$, $\Sigma^0\, \pi$, at low kaon energies ($0 \le p_K \le 153$ MeV/c) were treated in the K-matrix approach in the constant-scattering length approximation [12]. When $p_K > 153$ MeV/c , a phenomenological approximation of the data of the compilation [13] was used.

To estimate the Λ production cross sections in η- and ω-mesons rescattering processes (3) we made use of the following relations based on the assumption of the full validity of the consequences of SU(3)- symmetry for the cross sections:

$$\sigma(\eta p \Rightarrow \Lambda K^+) = 9/2\ \sigma(\bar{K}^0 p \Rightarrow \Sigma^0 \pi^+)$$
$$\sigma(\eta n \Rightarrow \Lambda K^0) = \sigma(\eta p \Rightarrow \Lambda K^+)$$
$$\sigma(\eta p \Rightarrow \Sigma^0 K^+) = \sigma(\eta n \Rightarrow \Sigma^0 K^0) = 1/2\ \sigma(\bar{K}^0\ p \Rightarrow \Lambda \pi^+) \qquad (8)$$

$$\sigma(\omega n \Rightarrow \Lambda K^0) = \sigma(\omega p \Rightarrow \Lambda K^+) = \sigma(\pi^- p \Rightarrow \Lambda K^0)$$
$$\sigma(\omega p \Rightarrow \Sigma^0 K^+) = \sigma(\omega n \Rightarrow \Sigma^0 K^0) = 1/3\ \sigma(\omega\ p \Rightarrow \Lambda K^+).$$

Of course, the validity of these relations, especially in the case of ω-mesons, is under question.

The total cross sections σ^{tot}_{MN} from (5) were taken from the compilations [11,13]. It was assumed, that $\sigma^{tot}(\eta N) = \sigma^{tot}(\omega N) = \tilde{\sigma}(\pi N)$, where $\tilde{\sigma}(\pi N)$ is some isospin averaged πN cross section fitted to the data [11].

We have also calculated K_S-meson production cross sections, σ_K , in $\bar{p}A$ -annihilation.

$$\sigma_K = \sigma_K(dir) + \sigma_K(as) - \sigma_K(abs). \qquad (9)$$

Here $\sigma_K(dir)$ is the cross section of direct K^0_S production in $\bar{p}N$-annihilation

$$\sigma_K(dir) = \sigma^{ann}_{\bar{p}A}(E_{\bar{p}})\ (\ W_p\ R^p_K(E_{\bar{p}}) + W_n\ R^n_K(E_{\bar{p}})), \qquad (10)$$

where $W_p(W_n)$ is the probability of annihilation on a bound proton (neutron). The value $\sigma_K(as)$ corresponds to the cross section of associated K-production with Λ in the reactions (1),(3). We also take into account the absorption of K in the reactions (2) (the term $\sigma_K(abs)$ in (9)). In principle, kaon charge exchange reactions, such as $K^+n \Rightarrow K^0p$, $K^-p \Rightarrow \bar{K}^0n$, should also be included into consideration. However, as we have checked, their contribution to the K^0_S production is practically negligible owing to the K^0_S being lost in the reverse charge exchange reactions.

The results of our calculations, as well as the existing experimental data, are collected in the Table.

Table. Cross sections of Λ and K^0_S-production in antiproton annihilation on different nuclei at 600 MeV/c. The cross sections $\sigma(M \to \Lambda)$, where $M=\pi,\eta,\omega,K$, stand for the contribution to the Λ production from rescattering of the corresponding mesons. The experimental data are from [1,2,10]

Cross sections (mb)	d	^{4}He	Ne
$\sigma^{ann}_{\bar{p}A}$	154.4 [14]	219.0 [15]	540. [1]
$\sigma(\pi \to \Lambda)$	0.002	0.007	0.037
$\sigma(\eta \to \Lambda)$	0.170	0.918	4.45
$\sigma(\omega \to \Lambda)$	0.023	0.127	0.99
$\sigma(K^- \to \Lambda)$	0.116	0.624	2.58
$\sigma(\bar{K}^0 \to \Lambda)$	0.120	0.670	2.76
$\sigma(\Lambda)$	0.431	2.35	10.80
$\sigma(K^0_S)$	2.77	3.96	10.10
$R=\sigma(\Lambda)/\sigma(K^0_S)$	0.156	0.592	1.1
$\sigma(\Lambda)_{exp}$	0.65±0.14	4.25±0.64	12.3±2.8
$\sigma(K^0_S)_{exp}$	3.74±0.56	4.51±0.60	5.4±1.1
R_{exp}	0.17±0.06	0.94±0.19	2.3±0.7

From inspection of the Table one can derive the following conclusions:

i) the overall agreement with the experimental data on Λ-production is satisfactory;

ii) the contribution from the rescattering of η- mesons is substantial (as large as the contribution from the kaon interaction). That is due to admixture of $s\bar{s}$-pairs in η-meson ;

iii) the contribution from pions is small due to the two-pion channels being only important ones in this low energy region.

In fact, the decrease of the Λ-production threshold due to the Fermi motion of the nucleons may also lead to some non-vanishing contribution from the three-pion annihilation channels. Owing to this possibility the Λ cross section may grow in the case of annihilation on helium and neon. Another factor which may also lead to an increase of Λ-production is the increase of the kaon branching ratios with the initial antiproton energy /16/.

We would like to note that in the framework of the "obligatory" single scattering approximation which we used one can quite naturally explain why the ratio $R=\sigma(\Lambda)/\sigma(K^0_S)$ for annihilation in neon at 600 MeV/c [1] is practically the same as for tantalum at 4 GeV/c [3]. In fact, in both cases annihilation takes place on the surface layer of the nucleus and the mesons always undergo inelastic interactions producing the Λ with the same probability which is practically independent of the nuclear dimensions. We anticipate that the same "saturation" for Λ-production must exist for all nuclei heavier than neon.

We conclude that simple rescattering of the annihilation mesons is sufficient to ensure a significant Λ-production even in the low energy region that is comfortably under the $\Lambda\bar{\Lambda}$ -threshold. The experimental data on exclusive and semi-inclusive reaction cross sections will be important for testing the rescattering model.

The existence of strong rescattering effects is the main characteristic feature of antiproton annihilation on nuclei. Precisely this feature is the main reason for the abundant yield of hypernuclei in $\bar{p}$A-annihilation, which may reach 10^{-4} hypernuclei per annihilation [17]. By analogy with the enhanced formation of Λ-hyperons, as suggested by S.A.Bunyatov, one can also expect that at higher energies the formation of charmed Λ_c^+ -hyperons will be also increased due to rescattering of the D-mesons formed in the antiproton annihilation. Therefore, it would be extremely interesting to search for supernuclei [18] formed by charmed baryons in antiproton annihilation with nuclei.

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