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

STRANGE PARTICLE PRODUCTION IN ANTIPROTON ANNIHILATION ON NUCLEI AT LOW ENERGIES

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

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1. INTRODUCTION

One of the most interesting questions of the physics of antiproton-nucleus interaction is the following: does annihilation in nuclear matter lead to the excitation of collective quark-hadron degrees of freedom of nuclei or can it be understood in terms of secondary interactions of the annihilation mesons with residual nucleons? One may hope that detailed experimental studies of the processes of strangeness production in $\bar{p}A$ - annihilation will clarify this complicated problem. The importance of such studies is based on an unexpectedly high Λ-hyperon production yield observed recently [1-5] in the annihilation of low energy antiprotons on nuclei. Thus, measurement of the production cross sections of Λ, $\bar{\Lambda}$ and K_S^0-mesons in the annihilation of antiprotons in Ta at 4 GeV/c [1] has revealed that $\sigma(\Lambda)$ is more than ten times greater, than the corresponding cross section for the $\bar{p}p \longrightarrow \Lambda\bar{\Lambda}$ reaction multiplied by $A^{2/3}$.

Still more surprising results were obtained in the PS 179 experiment at LEAR [2-4], in which the production of neutral strange particles was investigated in the annihilation of antiprotons on ^{20}Ne, ^{4}He and ^{3}He at 600 MeV/c and at rest. In this energy region the production of a Λ on a single nucleon is forbidden, since the $\bar{p}p \longrightarrow \Lambda\bar{\Lambda}$ reaction threshold is p_{th}=1435 MeV/c (associative Λ-production, such as $\bar{p}N \longrightarrow \Lambda K$, is obviously forbidden, too). Nevertheless, the Λ cross section turns out to be high, comparable or even greater than the cross section for the allowed K_S^0 production (the ratio $R=\sigma(\Lambda)/\sigma(K_S^0)$ is $R=2.3\pm0.7$ and 0.94 ± 0.19 for annihilation on ^{20}Ne and ^{4}He at 600 MeV/c, respectively). Unusually high yields (up to 10^{-3} per annihilation) of heavy hypernuclei were observed, also, in the PS 177 experiment at LEAR [6,7], where the annihilation of antiprotons stopping in ^{209}Bi and ^{238}U was investigated.

A number of models have been invoked to explain the high Λ production yield. Thus, Rafelski [8] has speculated about the possibility of the annihilation of a high energy antiproton penetrating deeply into the nucleus resulting in the formation at very low temperatures ($T \approx 60$ MeV) of some droplets of super-cooled quagma. The evaporation of these droplets should be characterized by an enhancement of strangeness production. Cugnon and Vandermeulen [9,10] have pointed out that increased strangeness production may occur not only because of the phase transition of hadronic matter but also owing to the evaporation of fireballs with non-zero baryonic number.

A lot of models [11-15] have tried to reproduce the characteristics of Λ production under the assumption that Λ's are produced in annihilation meson rescattering on one of the residual nucleons. However, due to the complexity of the problem the conclusions of different authors are not the same. For example, Ko and Yuan [12] were only able to predict 2/3 of the measured Λ cross section, whereas the authors of ref.[11] gave a Λ cross section approximately 20-30% higher than the experimental one.

In this article we report the results of calculations of Λ and K^0_S yields in $\bar{p}A$ annihilation at rest and in flight on different nuclei. Predictions concerning the $\Sigma^\pm$ cross sections as well as the different exclusive channels with kaons and hyperons are given.

2.DESCRIPTION OF THE MODEL

We have calculated the cross sections of Λ and K^0_S 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 have also considered the production of Λ in reactions with 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 probability of η- meson production in antiproton annihilation is quite significant and amounts to 7% of the total annihilation probability at low energies [16].

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

$$\bar{p} + N \Rightarrow \pi + \pi , \qquad \pi + N \Rightarrow \Lambda + K \qquad (1)$$

$$\bar{p} + N \Rightarrow K + \bar{K} + X, \qquad \bar{K} + N \Rightarrow \Lambda + m\pi ; \quad m = 1,2 \qquad (2a)$$

$$\bar{K} + N \Rightarrow \Sigma^0 + m\pi; \quad m = 1,2 \qquad (2b)$$

$$\bar{K} + N \Rightarrow \Sigma^\pm + m\pi; \quad m = 1,2 \qquad (2c)$$

$$\Sigma^\pm + N \Rightarrow \Lambda + N$$

$$\bar{K} + NN \Rightarrow \Lambda \; (\Sigma) + N \qquad (2d)$$

$$\bar{p} + N \Rightarrow \eta + X , \qquad \eta + N \Rightarrow \Lambda + K \qquad (3)$$

(here N stands for proton or neutron).

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 (2b) with Σ^0 production channels is due to the nearly 100% probability of the subsequent rapid $\Sigma^0 \Rightarrow \Lambda\gamma$ decay. It is important to take into account $\Sigma^\pm$ conversion into Λ (reactions (2c)) due to its high probability. For example, about 50% of the $\Sigma^\pm$ produced in the stopped K^- absorption in ^{12}C undergo conversion into Λ [17]. Two-body kaon absorption (2d) is also known to be important. Thus, for instance, its probability is 16 % and 22% in the stopped K^- absorption in ^{4}He and Ne, respectively (for review see ref. [18]).

Besides reactions (1)-(3) one can imagine some other sources of Λ's, for instance, $\omega + N \longrightarrow K + \Lambda$ or $\bar{K}^* + N \longrightarrow \Lambda + \pi$. However, ambiguities in the treatment of these reactions prevent their consideration (see below).

The relative yield of Λ production in the rescattering of annihilation mesons $MN \Rightarrow \Lambda K$ was calculated from the following expression:

$$Y_{\bar{p}A\Rightarrow\Lambda X}(E_{\bar{p}}) = \sigma_{\bar{p}A\Rightarrow\Lambda X}(E_{\bar{p}}) / \sigma^{ann}_{\bar{p}A}(E_{\bar{p}}) =$$

$$= \sum_M Y_M(E_{\bar{p}}) \int_{E_{th,M}} F(E_{\bar{p}}, E_M)\, W_\Lambda(E_{\bar{p}}, E_M)\, dE_M \qquad (4)$$

where $E_{\bar{p}}, E_M$ are the antiproton and meson total energies, respectively, $\sigma^{ann}_{\bar{p}A}(E_{\bar{p}})$ is the antiproton-nucleus annihilation cross section, $Y_M(E_{\bar{p}})$ is the relative probability of the meson M production in $\bar{p}$N-annihilation, $E_{th,M}$ is the threshold energy for the reaction MN ⇒ ΛX, $F(E_{\bar{p}}, E_M)$ is a function, normalized to unity, which describes the energy distribution of the annihilation mesons, and $W_\Lambda(E_{\bar{p}}, E_M)$ 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 have used for the energy distribution $F(E_{\bar{p}}, E_M)$ of annihilation kaons in the c.m.s. the parameterization from [19]:

$$F(E^*_M) = k\, E^*_M \exp(- E^*_M / T) \qquad (5)$$

with T=84 MeV. Here E^*_M and k are the center-of-mass total energy and momentum of the meson M. For eta mesons it was shown [11] that their momentum distribution is satisfactorily described by (5) with T = 110 MeV , the same as for pions [20]. Of course, in the case of Λ production by pions (1) we have used the energy distribution from two-pion annihilation but not the Boltzman-type spectrum (5).

The relative probabilities of meson production $Y_M(E_{\bar{p}})$ were taken from [16,21]. For our calculations it is very important to know the total kaon yield Y_K in $\bar{p}$p-annihilation at rest. However, this quantity is poorly known owing to difficulties in the identification of channels with charged kaons in bubble chambers. Thus, the frequently quoted value Y_K =6.82 ± 0.25 % was obtained in an old experiment [22], where $K^+K^-m\pi$ channels were not measured and the statistics on $K^0\bar{K}^0$ was poor. We used the value Y_K = 4.74 ± 0.22 % calculated in ref.[4] by summing up all measured annihilation channels with kaons with corresponding corrections for the charged modes. This value is in agreement with the result of ref. [23], which gives for all pionic modes of $\bar{p}$p annihilation at rest the value Y_π = 95.4 ± 1.8%. The energy dependence of the kaon yield was chosen in the form

$$Y_K = a + b*p_L \qquad (6)$$

The coefficients a and b were chosen to reproduce the 4.7% kaon yield for annihilation at rest and the 8.1% yield for annihilation at 700 MeV/c [24].

To determine the probability $W_\Lambda(E_{\bar{p}}, E_M)$ of Λ production in the case of antiproton annihilation on lightest nuclei (such as deuterium and helium) the following relation based on the simple picture of single rescattering of a on-shell meson [25] was applied :

$$W_\Lambda(E_{\bar{p}}, E_M) = (A-1)\, \frac{\sigma_{MN\Rightarrow\Lambda X}(E_M)}{4\pi} \left\langle \frac{1}{r^2_{NN}} \right\rangle \qquad (7)$$

where r_{NN} is the distance between the nucleons in the nucleus. It was estimated from the Hulthen type wave function for deuteron and from the factorized oscillator wave function in the case of ^{3}He and ^{4}He.

In the case of Λ production in $\bar{p}$ annihilation in heavy nuclei one cannot rely on the single rescattering approximation, so we have evaluated $W_\Lambda(E_{\bar{p}}, E_M)$ in the following way:

$$W_\Lambda(E_{\bar{p}}, E_M) = P_M(E_{\bar{p}}, E_M)\, \frac{\sigma_{MN\Rightarrow\Lambda X}(E_M)}{\sigma_{inel}(E_M)} . \qquad (8)$$

Here $P_M(E_{\bar{p}}, E_M)$ is the probability for an inelastic interaction of the meson M to occur with the bound nucleon and $\sigma_{inel}(E_M)$ is the meson-nucleon inelastic cross section.

We have calculated $P_M(E_{\bar p},E_M)$ under the assumption that the angular distribution of the annihilation mesons is isotropic in the c.m. frame, the nucleus was considered in the approximation of uniform density, and the annihilation point was taken to be precisely on the surface of the nucleus. Then

$$P_M(E_{\bar p},E_M) = \int d\Omega \; W(\Omega; E_{\bar p},E_M) \; \{ 1 - \exp(-\sigma_{inel}(E_M) \; T(\Omega)) \} \quad (9)$$

Here $W(\Omega;E_{\bar p},E_M)$ is the angular distribution of the annihilation meson in the lab. system, $T(\Omega)$ is the thickness function. In the case of annihilation in flight, eq.(9) is averaged over the antiproton impact parameter.

The cross section for Λ production by π-mesons was taken from ref.[26]. The cross section for reactions (2) $\bar K N \Rightarrow \Lambda \pi$, $\Sigma^0 \pi$, 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 [27]. When $p_K > 153$ MeV/c , a phenomenological approximation of the data of the compilation [28] on $\Lambda\pi$, $\Lambda\pi\pi$, $\Sigma\pi$, $\Sigma\pi\pi$ channels as well as $\bar K N$ inelastic cross section was applied. As an example, the results of the fit of $\sigma(K^-p \longrightarrow \Lambda$+neutrals) are shown in Fig.1. In all cases we used isospin averaged cross sections for meson scattering on a proton or neutron.

To estimate the Λ production cross sections in reactions (3) involving η-mesons we made the assumption that this process proceeds via s-channel resonances $\Lambda(1650)$ and $\Lambda(1710)$. These resonances exhibit significant coupling both to ηN and ΛK channels. To evaluate the ηN inelastic cross section one must also add a contribution from the $\Lambda(1535)$ resonance which couples strongly with the ηN channel. The resulting cross sections are shown in Fig.2 by long-dashed (σ_{tot}) and dotted ($\sigma(\eta n \Rightarrow \Lambda K)$ lines. However, the scarcity of experimental information about ηN interaction does not allow one to make any firm estimations of $\eta N \longrightarrow \Lambda K$ cross sections.

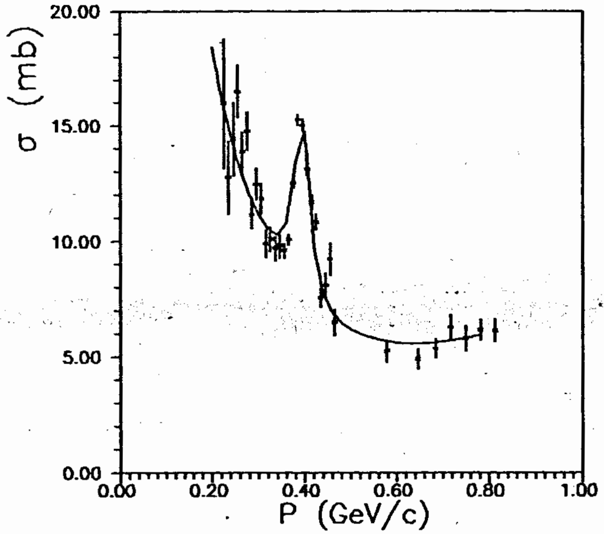

Fig.1 . Energy dependence of cross section for the reaction $K^- p \Rightarrow \Lambda$ + neutrals. Experimental points are from compilation [28], the solid line corresponds to the fit used in this calculation.

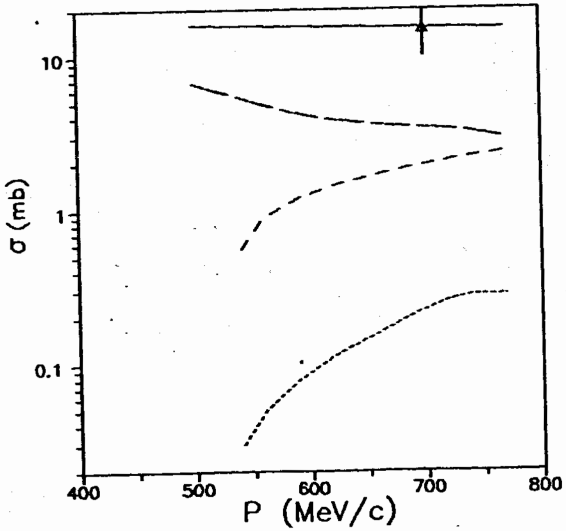

Fig.2 Energy dependence of the total ηN cross section and the cross section for the reaction $\eta N \Rightarrow \Lambda K$. Long-dashed and dotted lines correspond to calculations of $\sigma_{tot}(\eta N)$ and $\sigma(\eta N \Rightarrow \Lambda K)$ under the assumption of dominance of the s-channel resonances $\Lambda(1650)$ and $\Lambda(1710)$. Solid and dashed lines are the $\sigma_{tot}(\eta N)$ and $\sigma(\eta N \Rightarrow \Lambda K)$ cross sections normalised to the experimental point [31] σ_{tot}= 20 mb.

Even more serious ambiguities arise when attempts are made to take into consideration the Λ production due to ωN-interaction. In this case no s-channel resonances coupling with ωN or $3\pi N$ final states exist. This is why we prefer to omit ω-mesons rescattering whatsoever. We also have some doubts about the necessity of taking into account the contribution from K^* rescattering. The reason is that the relatively large width of K^* prevents interaction with a nucleon before its decay. However, even the small interaction probability of K^* may be significant for reactions with double strangeness production.

We have also calculated the K_S-meson production yield in $\bar{p}A$ -annihilation.

$$Y_{K_S} = \sigma_{\bar{p}A \Rightarrow K_S X}(E_{\bar{p}}) / \sigma^{ann}_{\bar{p}A}(E_{\bar{p}}) = Y_{K_S}(dir) + Y_{K_S}(as) - Y_{K_S}(abs) \quad (11)$$

Here $Y_{K_S}(dir)$ is the total K^0_S yield from K^0 and $\bar{K}^0$ production in $\bar{p}N$-annihilation

$$Y_{K_S}(dir) = 7/16\ Y_K \quad (12)$$

where Y_K is the total yield of kaons from (6).

The value $Y_{K_S}(as)$ corresponds to associated K-production with Λ in reactions (1) and (3). We also take into account the K absorption in reactions (2) (the term $Y_{K_S}(abs)$ in (11)). This was done in the same manner as for Λ production calculations with substitution in (7)-(8) of $\sigma_{inel}(E_M)$ for $\sigma_{MN \Rightarrow \Lambda X}(E_M)$. In principle, kaon charge exchange reactions, such as $K^+n \Rightarrow K^0p$, $K^-p \Rightarrow \bar{K}^0n$, should also be included into the consideration. However, we have verified their contribution to the K^0_S production to be practically negligible owing to the K^0_S being lost in the inverse charge exchange reactions.

For better determination of the Λ production mechanism the information concerning different exclusive channels is of great importance. We have calculated the cross sections of different semi-exclusive reactions with two kaons or a kaon-hyperon pair in the final state. For example, the cross sections for the $K^0_SK^0_SX$ and ΛK^0_SX channels are the following:

$$\sigma(K^0_S\ K^0_S) = \sigma_{ann}(\bar{p}A)\ Y(K^0_S\ K^0_S)\ (\ 1 - X_K) \quad (13)$$

where $Y(K^0_SK^0_S)$ is the yield of $K^0_SK^0_S$ in the $\bar{p}p$ annihilation and X_K is the fraction of absorbed kaons.

For the ΛK^0_S channel we have:

$$\sigma(\Lambda K^0_S) = 1/2\ \sigma_{ann}(\bar{p}A)\ (C_1 + C_2) \quad (14)$$

where

$$C_1 = (Y_\pi\ W(\pi N \Rightarrow K^0\Lambda) + Y_\eta\ W(\eta N \Rightarrow K^0\Lambda))$$
$$C_2 = Y_{K^0}\ W(\bar{K}N \Rightarrow \Lambda X) \quad (15)$$

Here $W(MN \Rightarrow \Lambda X)$ are energy averaged probabilities for Λ creation by MN rescattering and Y_M stands for meson branching ratios (see (4)). Similar relations for $K^+K^0_S$ or ΛK^+ channels are readily derived in the same manner as (13)-(15).

3. DISCUSSION OF RESULTS

The results of calculations of the Λ yield $Y(\Lambda)$ for antiproton annihilation at rest are shown by asterisks in Fig.3. The contributions from reactions (1),(2a)-(2c),(3) were considered. To take into account the contribution from $\Sigma^\pm N \Rightarrow \Lambda N$ conversion we assumed the conversion probability $C_{\Sigma \Rightarrow \Lambda}$ to be 0.5 in the case of annihilation on nuclei with $A \geq 12$. This is motivated by data on the absorption of stopping kaons [17]. In the case of $\bar{p}$ annihilation on the lightest nuclei we set $C_{\Sigma \Rightarrow \Lambda} = 0$.

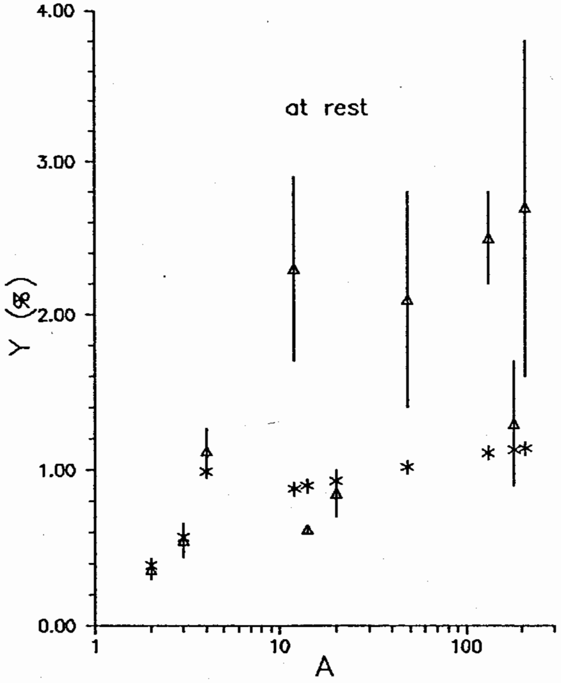

Fig.3 The yield Y(Λ) of Λ-hyperons produced in $\bar{p}A$ annihilation at rest. The results of calculations are shown by asterisks. The experimental data are from refs. [2-5,29,30].

One can see that the A dependence of Y(Λ) is significant only for the lightest nuclei where Y(Λ) grows with the number of nucleons in the residual nucleus. In the case of heavier nuclei some kind of saturation occurs and the calculated Y(Λ) increases only by 30% from Ne to Pb. The agreement with the experimental data on Y(Λ) for the lightest nuclei is quite good. Some underestimation of Y(Λ) for ^{12}C, ^{48}Ti, Xe and Pb may be due to these data [5,29] having actually been obtained not for stopping antiprotons but for antiprotons in the 0-450 MeV/c [29] or 0-300 MeV/c [5] regions. An admixture of high energy antiprotons should lead to an enhancement of the Λ production owing to the kaon yield increasing with the antiproton energy. The experimental data [2,30] from good quality LEAR beams for annihilation on ^{14}N and Ne are approximately two times smaller, than those of ref. [5,29], and our calculations describe them satisfactorily.

It is interesting to analyze the respective contributions to Y(Λ) of the rescattering of different mesons. It turns out, that the contribution from pions is small (< 1% of Y(Λ)), because only the energy of pions from two-pion channels is higher, than the Λ production threshold T_{th}= 758.4 MeV. The branching ratio of $\bar{p}p \longrightarrow \pi\pi$ is small, of the order of 3.7 10^{-3} [21].

The contribution from η,ω and other heavy mesons depends strongly on the model adopted for their interaction with nucleons. As we have mentioned earlier, the scarcity of experimental information leads to ambiguity in the significance of the heavy mesons rescattering. Thus, in ref.[11] the contribution to the Λ yield from η meson rescattering was estimated to be 5.6 %. The following simple relation between $\pi N \longrightarrow \Lambda K$ and $\eta N \longrightarrow \Lambda K$ cross sections was adopted:

$$\frac{\sigma\ (\pi N \longrightarrow \Lambda K)}{\sigma\ (\eta N \longrightarrow \Lambda K)} = \frac{k}{k_\eta} \tag{16}$$

where k and k_η are the pion and η-meson c.m. momenta, respectively.

In [14] we estimated the ηN cross section on the basis of SU(3) symmetry relations which predict that at low energies $\sigma(\eta N \longrightarrow \Lambda K)$ is comparable with $\sigma(KN \longrightarrow \Lambda\pi)$ and that the contribution of reaction (3) is up to 40% of the total Λ yield in $\bar{p}A$ annihilation. However, the reliability of SU(3) relations at low energies is under question.

If we evaluate the ηN cross sections assuming dominance of the s-channel resonances in ηN scattering, then $\sigma_{tot}(\eta N)$ and $\sigma(\eta N \longrightarrow \Lambda K)$ are small (see, long-dashed and dotted lines in Fig.2) and the corresponding contribution to the Λ yield is negligible (< 1%). However, as one can see in Fig.2 , the only experimental point [31] on $\sigma_{tot}(\eta N)$ existing in this energy interval lies higher than the resonance dominance model predictions. So, to test the sensitivity of the results to the possible η rescattering contribution we fixed $\sigma_{tot}(\eta N)=20$ mb, as in ref.[31], and scaled $\sigma(\eta N \longrightarrow \Lambda K)$ correspondingly (see, solid and dashed lines in Fig.2). The resulting contribution to the Λ yield for antiproton annihilation at rest is shown by the dotted line in Fig.4. One can see that it is also rather small, being of the order of 10% of the total $Y(\Lambda)$.

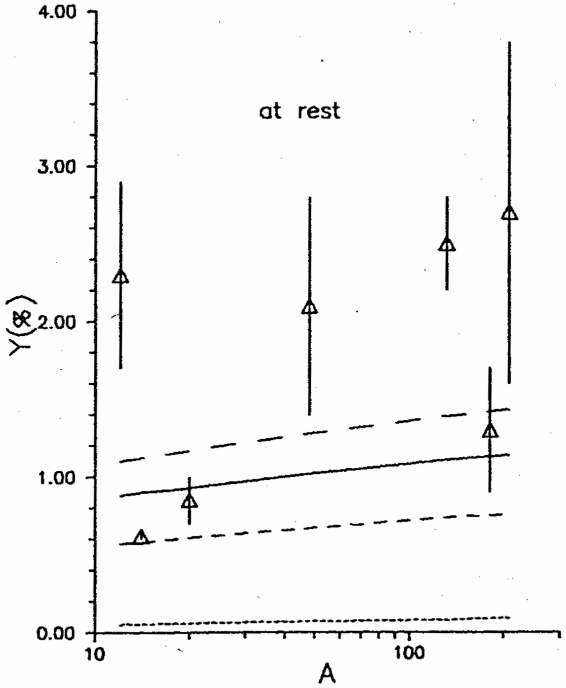

Fig 4. Contributions of different processes to the formation of Λ-hyperons. The dotted line shows the contribution from η rescattering (3). "Direct" Λ production in reactions (2a)-(2b) is shown by the dashed line. The solid line corresponds to the sum of direct Λ and Σ^0 production (2a)-(2b) and the rescattering of charged Σ's (2c). If the contribution from $\bar{K} + NN \Rightarrow Y + N$ absorption is also added, the results are represented by the long-dashed line.

It turns out that the most significant contribution to Λ production is due to $\bar{K}$ rescattering. In Fig.4 the "direct" Λ production in reactions (2a)-(2b) is shown by the dashed line. The solid line corresponds to the sum of direct Λ and Σ^0 production and the rescattering of charged Σ's (2c). In principle, a contribution from $\bar{K} + NN \Rightarrow Y + N$ absorption (2d) may also be added. If one assumes the probability of two-body kaon absorption to be 20 %, as indicated in ref. [18], then the corresponding $Y(\Lambda)$ will be elevated up to the level shown in Fig.4 by the long-dashed line.

From inspection of Fig.4 it is clear that the rescattering of kaons in the reactions $\bar{K}N \longrightarrow \Lambda X$, $\Sigma^0 X$ is sufficient to ensure a significant Λ production, of an order of magnitude comparable to the experimentally observed one. However, at least two other strong channels for Λ production exist: two-body kaon absorption (2d) and $\Sigma^{\pm}$ charge exchange (2c). To fix precisely the role of these mechanisms more experimental data on different exclusive channels are required.

It should be noted, that along with Λ and Σ^0 many charged Σ should be produced in the kaon rescattering. In Fig.5 the yield of $\Sigma^{\pm}$ (dashed line) is compared with that of Λ (full line). Bearing in mind the significant hypernucleus formation rate registered in $\bar{p}A$ annihilation at rest [6,7] one may conclude that antiproton-nucleus annihilation should also be a good source for Σ-hypernuclei production. Moreover, the momentum distribution of annihilation kaons has a peak at $\cong$ 400 MeV/c, which is near to the "magic" momentum ($\cong$ 280 MeV/c) for Σ recoilless production. This fact makes Σ -hypernucleus production in $\bar{p}A$ annihilation favorable. This possibility is still unexplored in the experiments.

The dependence of the Λ yield on the initial $\bar{p}$ momentum is shown in Fig.6 . One can see that the character of the energy dependence of $Y(\Lambda)$ differs for different nuclei.

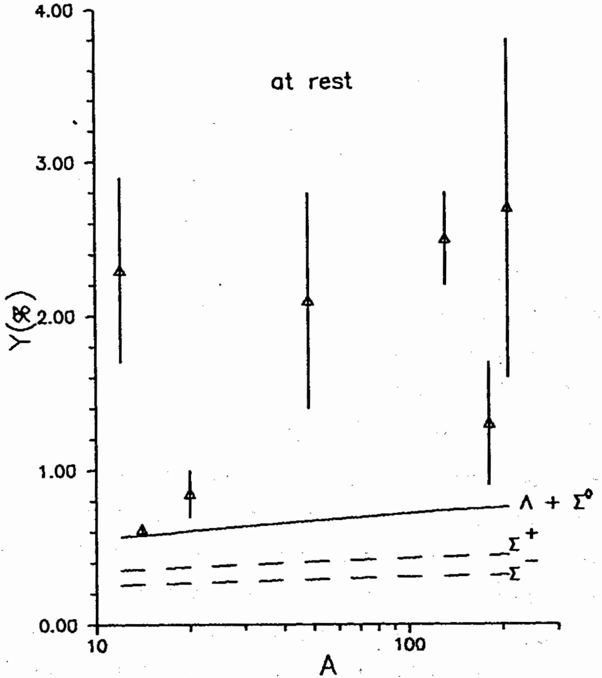

Fig.5. Yields of $\Sigma^{\pm}$ hyperons in $\bar{p}A$ annihilation at rest (dashed lines). A part of the Σ^{-} is converted into Λ's in rescattering on nucleons of the residual nucleus. The solid line corresponds to the yield of Λ hyperons.

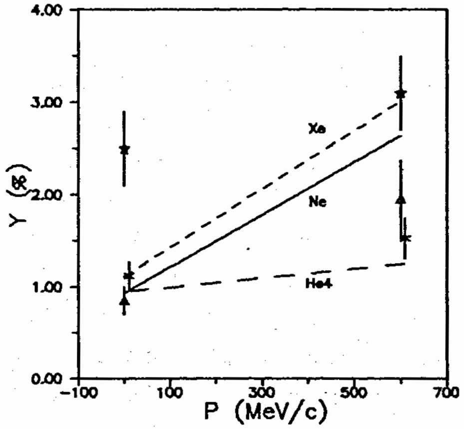

Fig.6. Energy dependence of the cross sections of Λ production in $\bar{p}$ annihilation on different nuclei. Theoretical predictions are shown by solid (Ne), dashed (Xe) and long-dashed (^{4}He) lines. The experimental points for Ne (triangles) are from ref.[2], for ^{4}He (crosses) are from ref.[2-3] and for Xe (stars) are from ref.[5]

Thus, for light nucleus, like ^{4}He , Y(Λ) in the main follows the energy dependence of the kaon yield in $\bar{p}p$ annihilation (6). In the case of $\bar{p}$ annihilation on heavy nuclei the increase of Y(Λ) with energy is more substantial. The main reason for this is the increase of the "acceptance" factor $P_M(E)$ (9) with energy, i.e. the part of the solid angle in the kaon angular distribution covered by the nucleus grows with energy owing to the shrinkage of the angular distribution in the forward direction. Note that the data of ref.[5] for Y(Λ) in Xe demonstrate a very weak energy dependence (see Fig.5). It may be a reflection of the averaging over energy due to the initial beam spreading out in the experiment [5], as mentioned above.

In Table 1 the yield of K_S in $\bar{p}A$ annihilation on different nuclei is compared with the results of calculations .

Table 1. The yield of K_S $Y(K_S) = \sigma(K_S)/\sigma(\mathrm{ann})$ in $\bar{p}A$ annihilation on different nuclei for stopping $\bar{p}$ and at 600 MeV/c. The experimental data are from refs.[2-5,32].

A	Theory $Y(K_S)$ %	Experiment $Y(K_S)$%	Theory $Y(K_S)$ %	Experiment $Y(K_S)$%
	A T R E S T		6 0 0	MeV/C
^{2}H	1.80		3.06	2.42±0.36
^{3}He	1.67	1.59 ± 0.20	2.84	
^{4}He	1.38	1.07 ± 0.11	2.34	1.63±0.22
^{20}Ne	1.76	0.72 ± 0.12	2.57	0.85±0.17
^{131}Xe	1.72	2.1 ± 0.23	2.47	2.0± 0.2

One can see that in the case of $\bar{p}^4$He and $\bar{p}$Ne annihilation the experimental values of $Y(K^0_S)$ are lower than the theoretical ones. These differences is worth a special discussion. Let us assume equal probabilities for all combinations of $K\bar{K}$ pair production in $\bar{p}N$ annihilation, then

$Y(K^0_S)$ is related to the total yield of kaons Y_K as follows:

$$Y(K^0_S) = \frac{7 - 3\,x_K}{16}\,Y_K \qquad (17)$$

The parameter x_K stands for the probability for a kaon to be absorbed in the nucleus. In our calculations the value of x_K is no more than 0.35-0.4 . If one assumes that all $\bar{K}$'s are absorbed , i.e. $x_K=1$, then $Y(K^0_S) = 1/4\ Y_K$. Therefore, even in the case of complete absorption of all $\bar{K}$'s it is impossible to explain the experimental yields $Y(K^0_S)$ that are smaller than 1% assuming $Y_K=4.7\%$. The data on $Y(K^0_S)$ in ^{4}He and Ne may be regarded as an indication of suppression of the total strangeness yield Y_K in $\bar{p}A$ annihilation as compared with the $p\bar{p}$ case.

The reasons for such suppression may lie in the decrease of the overall strangeness yield in antiproton annihilation in gases. It was clearly demonstrated in the experiments of ASTERIX [34-36] that the yields of different kaon channels like K^+K^-, $\pi\Phi(\Phi \Rightarrow K^+K^-)$, $\omega\Phi(\Phi \Rightarrow K^+K^-)$, $\pi^+\pi^-E$ $(E \Rightarrow K^{\pm}K^0\pi^{\mp})$ are smaller when stopping antiprotons annihilate in gaseous hydrogen in comparison with annihilation in liquid hydrogen. The main physical reason for the decrease of kaon yields in the hydrogen gas may be the large probability (≈ 50%) of annihilation from P-states. It is rather natural to assume [37] that annihilation into kaons should be a more short-ranged process than annihilation into pions. Thus, the kaon production should demand more overlapping of the $N\bar{N}$ quark bags, which is more likely to accomplish from S-states than from P-states.

To check the hypothesis the direct measurements of many kaon channels of antiproton annihilation in gases are needed. At present, due to lacking of experimental information it is not known to what (if any) extent the total kaon production in gases is suppressed .

In Table 2 a comparison between the experimental and theoretical yields of $K^0_SK^0_S$, $K^+K^0_S$, ΛK^+ and ΛK^0_S in $\bar{p}A$ annihilation is presented.

Table 2. The yields of some semi-exclusive channels of strange particle production in $\bar{p}A$ annihilation at rest. The experimental data are from refs.[3-5,29,33]

A	Theory $Y(\Lambda K_S)$	Experiment $Y(\Lambda K_S)$	Theory $Y(K_SK_S)$	Experiment $Y(K_SK_S)$
at rest				
^{2}H	0.17	0.123 ± 0.07	0.21	
^{3}He	0.26	0.15 ± 0.08	0.16	0.20 ± 0.09
^{4}He	0.44		0.06	
^{131}Xe	0.42	1.25 ± 0.3	0.17	0.28 ± 0.11
600 MeV/c				
^{4}He	0.73	0.07 ± 0.07	0.11	0.25 ± 0.15
^{131}Xe	1.14	1.40 ± 0.32	0.14	0.19 ± 0.08
A	Theory $Y(\Lambda K^+)$	Experiment $Y(\Lambda K^+)$	Theory $Y(K_SK^+)$	Experiment $Y(K_SK^+)$
at rest:				
^{2}H	0.34	0.107 ± 0.007		
^{131}Xe	0.84	0.76 ± 0.20	0.34	0.24 ± 0.08
600 MeV/c				
^{131}Xe	2.3	1.00 ± 0.20	0.28	0.26 ± 0.07

One can see that the theoretical predictions are in good agreement with the experimental data on $K^0_SK^0_S$ and K_SK^+ . As far as channels with Λ are concerned, the agreement is also satisfactory, except in the case of $Y(\Lambda K_S)$ in ^{4}He at 600 MeV/c (where, in fact, only a single ΛK_S event was observed) and of some points for Xe. But the experimental statistics [5] is still insufficient to draw any definite conclusions from these differences.

Nevertheless, the data of ITEP [5] could provide valuable information, because for the first time several different strange particle production channels have been measured. This makes it possible to check some obvious relations that should hold within the conventional production scheme of annihilation kaons followed by rescattering in the nucleus. In this model the numbers of absorbed K^- and $\bar{K}^0$ should be equal (under the assumption of equal production probabilities for all combinations of charged and neutral kaons). So the yields of Λ associated with K^0 and of Λ associated with K^+ should be the same. The ratios between the yields of different channels with neutral and charged kaons in $\bar{p}A$ annihilation should also be the same as in the case of annihilation on a free nucleon. In the Table 3 we compare some ratios between semi-exclusive channels obtained in ref.[5] with those expected in the rescattering model.

Table 3.Comparison of the ratios between different semi-exclusive channels with two strange particles obtained in $\bar{p}$Xe annihilation [5] and in annihilation on free nucleons.

Ratio	$\bar{p}$ Xe at rest	$\bar{p}$ Xe 600 MeV/c	$\bar{N}N$
$K_SK_S/\ K_SK^-$	0.58 ± 0.34	0.76 ± 0.49	0.5
$K_SK^-/\ K_SK^+$	2.00 ± 1.10	0.96 ± 0.53	1.0
$K^+K^-/\ K_SK^+$	1.79 ± 1.39	2.10 ± 1.12	2.0
$\Lambda K_S/\ \Lambda K^+$	1.64 ± 0.59	1.40 ± 0.41	0.5

One can see that, indeed, the ratios between yields of different kaon channels in $\bar{p}A$ annihilation is the same as for $\bar{N}N$. The only difference is that, according to the data of ref.[5], the Λ's prefer being created with K_S^0, but not with K^+. If this difference is confirmed by large statistics (only a quarter of all the events obtained in the ITEP experiment has been processed up to now), then a possible explanation may be the following. The annihilation in Xe takes place mainly in the surface region of the nucleus , presumably, enriched by neutrons. Annihilation on neutrons should lead to an increase in the production probabilities of $K^0K^-m\pi$ and $K^0\bar{K}^0m\pi$ channels, as compared with $K^+K^-m\pi$ and $K^+\bar{K}^0m\pi$. In this case the subsequent rescattering of kaons will provide more Λ's associated with neutral kaons, than with K^+.

4.CONCLUSIONS

We conclude that simple rescattering of annihilation mesons suffices to ensure a significant Λ-production yield even in the low energy region essentially below the $\Lambda\bar{\Lambda}$ -threshold. Certainly, no enhancement of strangeness production in $\bar{p}A$ annihilation exists; on the contrary, one may speculate on the suppression of strangeness production in the case of $\bar{p}$ annihilation in ^{4}He, ^{14}N and Ne gases.

The main source of the abundant hyperon production is the rescattering of annihilation kaons in reactions (2a)-(2c). Subsequent transformations of charged Σ into Λ due to secondary interactions with nucleons of the residual nucleus are also important. Processes involving kaon absorption, like (2d), may also contribute to Λ production. The production of Λ in the rescattering of pions, η or other heavy mesons gives a small contribution but this should be important in producing Λ's with high momenta.

The rescattering scheme is capable of satisfactory reproduction of the yield of semi-inclusive annihilation channels with two strange particles in the final state. It provides additional substantiation for the importance of final state interactions of annihilation mesons.

The possible suppression of strangeness production in $\bar{p}A$ annihilation in gases may represent a reflection of some dynamical selection rules which preventing annihilation into strange mesons from states of high angular momenta. However, more complete and precise experimental data on exclusive and semi-inclusive reactions involving strange particles are required to verify the existence of this phenomenon.

The discovery of the high yield of hyperons in low energy $\bar{p}A$ annihilation is very important for apprehending the role of annihilation meson rescattering effects. It provides the best and clear indication that these effects are by no means negligible and may be used for investigation of the interaction of annihilation mesons with nucleons, in studies of the formation of Λ- and Σ-hypernuclei, for searching for multiquark states, like H-particles, and even for studying supernucleus formation by slow charmed hyperons appearing as the result of rescattering in the nucleus of different charmonium states produced in $\bar{p}A$ annihilation [38].

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Рождение странных частиц при аннигиляции
антипротонов на ядрах при низких энергиях

Анализируются экспериментальные данные по рождению Λ и K^0_s-мезонов при аннигиляции антипротонов на ядрах при низких энергиях ($E_{\bar{p}}$<200 МэВ) для выяснения вопроса о том, наблюдается ли в антипротон-ядерной аннигиляции дополнительное (по сравнению с pp аннигиляцией) рождение странных частиц. Оказывается, что простое перерассеяние аннигиляционных мезонов способно обеспечить значительный выход Λ-гиперонов даже при очень низкой энергии под порогом рождения $\Lambda\bar{\Lambda}$. Никакого увеличения рождения странных частиц в $\bar{p}$A аннигиляции не происходит, напротив, можно говорить о подавлении рождения странности в случае аннигиляции $\bar{p}$ в газах ^{4}He, ^{14}N и Ne. Основным источником обильного рождения гиперонов являются аннигиляционные каоны. Модель перерассеяния оказывается способной объяснить также вероятности полуинклюзивных каналов аннигиляции с двумя странными частицами в конечном состоянии.

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Kharzeev D.E., Sapozhnikov M.G. E4-91-104
Strange Particle Production in Antiproton
Annihilation on Nuclei at Low Energies

The experimental data on the Λ and K^0_s-meson production in antiproton annihilation on nuclei at low energies ($E_{\bar{p}}$< 200 MeV) are analyzed in order to understand is there some additional (in comparison to the pp case) production of strange quark pairs in antiproton-nucleus annihilation. We conclude that simple rescattering of annihilation mesons suffices to ensure a significant Λ-production yield even in the low energy region essentially below the $\Lambda\bar{\Lambda}$-threshold. Certainly, no enhancement of strangeness production in $\bar{p}$A annihilation exists; on the contrary, one may speculate on the suppression of strangeness production in the case of $\bar{p}$ annihilation in ^{4}He, ^{14}N, and Ne gases. The main source of the abundant hyperon production is the rescattering of annihilation kaons. The rescattering scheme is capable of satisfactory reproduction of the yield of semi-inclusive annihilation channels with two strange particles in the final state.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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